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CONTAMINANTS AND REMEDIAL OPTIONS AT SELECTED METAL-CONTAMINATED SITES

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Project Officer
Michael D. Royer
Technical Support Branch
Superfund Technology Demonstration Division
National Risk Management Research Laboratory
Edison, New Jersey 08837

NATIONAL RISK MANAGEMENT RESEARCH LABORATORY
OFFICE OF RESEARCH AND DEVELOPMENT
U.S. ENVIRONMENTAL PROTECTION AGENCY
CINCINNATI, OHIO 45268

NOTICE

This review of contaminants and remedial options at selected metal-contaminated sites summarizes information collected from U.S. Environmental Protection Agency (EPA) programs, peer-reviewed journals, industry experts, vendor data, and other sources. A variety of potential candidate treatment technologies are described as advisory guidance to assist in identifying feasible treatment technologies.

The information in this document has been funded in part by EPA under Contract No. 68-CO-0003, Work Assignment 41, to Battelle (Columbus Division). It has been subject to the Agency's peer and administrative review, and it has been approved for publication as an EPA document. Mention of trade names or commercial products does not constitute endorsement or recommendation for use.

Compliance with environmental and occupational safety and health laws is the responsibility of each individual site manager and is not the focus of this document.

FOREWORD

The U.S. Environmental Protection Agency is charged by Congress with protecting the Nation's land, air, and water resources. Under a mandate of national environmental laws, the Agency strives to formulate and implement actions leading to a compatible balance between human activities and the ability of natural systems to support and nurture life. To meet these mandates, EPA's research program is providing data and technical support for solving environmental problems today and building a science knowledge base necessary to manage our ecological resources wisely, understand how pollutants affect our health, and prevent or reduce environmental risks in the future.

The National Risk Management Research Laboratory is the Agency's center for investigation of technological and management approaches for reducing risks from threats to human health and the environment. The focus of the Laboratory's research program is on methods for the prevention and control of pollution to air, land, water, and subsurface resources; protection of water quality in public water systems; remediation of contaminated sites and groundwater; and prevention and control of indoor air pollution. The goal of this research effort is to catalyze development and implementation of innovative, cost-effective environmental technologies; develop scientific and engineering information needed by EPA to support regulatory and policy decisions; and provide technical support and information transfer to ensure effective implementation of environmental regulations and strategies.

This publication has been produced as part of the Laboratory's strategic long-term research plan. It is published and made available by EPA's Office of Research and Development to assist the user community and to link researchers with their clients.

E. Timothy Oppelt, Director
National Risk Management Research Laboratory

ABSTRACT

This document provides information that facilitates characterization of the site and selection of treatment technologies at metal-contaminated sites that are capable of meeting site-specific cleanup levels. The document does not facilitate the determination of cleanup levels. This document will assist Federal, State, or private site removal and remedial managers operating under Comprehensive Environmental Response, Compensation, and Liability Act (CERCLA), Resource Conservation and Recovery Act (RCRA), or state regulations.

This document focuses mainly on the metalloid arsenic and the metals cadmium, chromium, lead, and mercury. Other metals are discussed, particularly those that have a strongly favorable or unfavorable influence on the performance of a treatment technology.

The remedial manager faces the challenge of selecting remedial options that meet established cleanup levels. A wide range of physical, chemical, and thermal process options are available for remediation of metal-contaminated sites. These options can reduce mobility, reduce toxicity, or allow separation and concentration of metal contaminants. No single process option can remediate an entire metal-contaminated site. The remedial manager must combine pretreatment and posttreatment components to achieve the best performance by the principal process option.

This document is designed for use with other remedial guidance documents issued for RCRA, CERCLA, and/or State-mandated cleanups to accelerate the remediation of metal-contaminated sites.

Sections describing contaminants at metal-contaminated sites and the behavior, fate, and transport of metals in the environment are provided to assist the remedial manager in identifying the matrix and chemical species likely to be present. The section on remedial options outlines the arrangement of treatment trains to achieve performance levels. Technology performance data provided can help the remedial manager narrow options to those most likely to achieve site-specific cleanup goals. The descriptions of remedial options cover innovative and emerging technologies, as well as proven treatments.

Some standard information sources on containment and water treatment technologies are indicated. These technology areas are not covered in this document because they are thoroughly discussed in other documents.

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ABBREVIATIONS AND SYMBOLS

AA	atomic absorption spectroscopy (a microcharacterization method)
AERC	Advance Environmental Recycling Corporation
AETS	Acid Extraction Treatment System
Ag	silver
ANC	Acid Neutralization Capacity (test)
ANS	American Nuclear Society
ANSI	American National Standards Institute
ANSI/ANS/16.1	American Nuclear Society test 16.1, a leaching test
AOC	area of contamination
APC	air pollution control
API	American Petroleum Institute
ARARs	applicable or relevant and appropriate requirements
ART	Alternative Remedial Technologies, Inc.
As	arsenic
ASH	Air-Sparged Hydrocyclone
ASTM	American Society for Testing and Materials
ATR	Annotated Technical Reference
ATTIC	Alternative Treatment Technology Information Center
AVIP	Advanced Vitrification/Incineration Process
BACT	Best Available Control Technology
BBS	Bulletin Board System
BDAT	Best Demonstrated Available Technology (RCRA treatment standard)
BDL	below detection limits
BESCORP	Brice Environmental Services Corporation
BMRC	Bureau of Mines Research Center
BNA	base, neutral, and acid (organic) compounds
BOM	U.S. Bureau of Mines
BTU, Btu	British thermal unit
CA	corrective action
CAA	Clean Air Act
CALMAX	California Materials Exchange
Cal WET	California Waste Extraction Test, a leaching test.
CAMU	Corrective Action Management Unit
CB	cement-bentonite
CCBA	Coordinate, Chemical Bonding, and Adsorption (process)
CCJ	Campbell Centrifugal Jig
CCR	Chromated Copper Arsenate
Cd	cadmium
CDI	chronic daily intake
CEAM	Center for Exposure Assessment Modeling
CEC	cation exchange capacity
CEP	catalytic extraction process
CERCLA	Comprehensive Environmental Response, Compensation, and Liability Act of 1980
CERCLIS	Comprehensive Environmental Response, Compensation, and Liability Information System
CFR	Code of Federal Regulations
CLP	Contract Laboratory Procedures

ABBREVIATIONS AND SYMBOLS (CONTINUED)

CLU-In	Cleanup Information (Electronic Bulletin Board)
CMS	Cyclone Melting System
CNS	central nervous system
COD	chemical oxygen demand
COE	U.S. Army Corps of Engineers
CORA	Cost of Remedial Action (software package)
CPS	cancer potency slope
Cr	chromium
Cr(VI)	hexavalent chromium
CRN	Core Research Needs for Containment Systems
CRV	Counter Rotating Vortex combustor
CSH	Calcium Silicate Hydrate
CWA	Clean Water Act
DLT	Dynamic Leach Test
DOE	U.S. Department of Energy
DQO	Data Quality Objective
DRE	destruction-removal efficiency
DTPA	diethylenetriaminepentaacetic acid
EAF	electric arc furnace
EDTA	ethylenediaminetetraacetic acid
EDXA	energy dispersive X-ray analysis, a microcharacterization method.
EE/CA	Economic Evaluation/Cost Analysis
Eh	oxidation reduction potential
ELT	Equilibrium Leach Test
EPA	U.S. Environmental Protection Agency
EP Tox	Extraction Procedure Toxicity Test
ESD	electro-acoustic soil decontamination
FDA	Food and Drug Administration
FGD	flue gas desulfurization
FR	Federal Register
FS	Feasibility Study
FTIR	Fourier transform infrared spectroscopy
FY	fiscal year
GC/MS	gas chromatography/mass spectrometry
GI	gastrointestinal
GW	groundwater
HCB	hexachlorobenzene
HELP	Hydrologic Evaluation of Landfill Performance
Hg	mercury
HI	hazard index
HQ	hazard quotient
HRD	Horsehead Resource Development Company
HRS	Hazard Ranking System
HSL	Hazardous Substance List
HSWA	Hazardous and Solid Waste Amendments of 1984
HTMR	high-temperature metal(s) recovery
HWSDC	Hazardous Waste Superfund Data Collection
ICP	inductively coupled plasma atomic emission spectroscopy.
ID	identification
IGWMC	International Ground Water Modeling Center

ABBREVIATIONS AND SYMBOLS (CONTINUED)

INEL	Idaho National Engineering Laboratory
INMETCO	International Metals Reclamation Corporation
IRIS	Integrated Risk Information System
IRM	iron-rich material
ISV	in situ vitrification
IWT	International Waste Technologies
kWh	kilowatt hours
LAER	Lowest Achievable Emission Rate
LDR	Land Disposal Restriction
LIMB	Lime Injection Multistage Burner
LRT	Liquid Release Test
Mb	molybdenum
MCL	maximum contaminant level; maximum concentration limit
MCLG	maximum contaminant limit goal
MEP	Multiple Extraction Procedure
m_{eq}	milliequivalent
MIBC	methyl isobutyl carbinol (a synthetic frother)
μm	micrometer(s)
mm	millimeter(s)
mV	millivolt(s)
MSDS	Material Safety Data Sheet
MSW	municipal solid waste
MTRs	minimum technology requirements
MWEP	Monofilled Waste Extraction Procedure
NAAQS	National Ambient Air Quality Standards
NAPL	nonaqueous-phase liquid
NCC	National Computer Center
NCEL	Naval Civil Engineering Laboratory
NCP	National Oil and Hazardous Substances Contingency Plan
NEESA	Naval Energy and Environmental Support Activity
NESHAP	National Emissions Standard for Hazardous Air Pollutants
NIOSH	National Institute for Occupational Safety and Health
NJDEP	New Jersey Department of Environmental Protection
NMR	nuclear magnetic resonance spectroscopy
NPDES	National Pollutant Discharge Elimination System
NPL	National Priorities List
NRC	National Research Council; U.S. Nuclear Regulatory Commission
NSPS	New Source Performance Standards
NSR	National Smelting and Refining Company
NYSC-HWM	New York State Center for Hazardous Waste Management
OAQPS	Office of Air Quality Planning and Standards (of the U.S. EPA)
O&M	operations and maintenance (costs)
OERR	Office of Emergency and Remedial Response
OLS	Online Library System (of EPA)
OR&N	oxidation, reduction, and neutralization
OSHA	Occupational Safety and Health Act; Occupational Safety and Health Administration
OSW	Office of Solid Waste
OSWER	Office of Solid Waste and Emergency Response
OTS	Office of Toxicological Substances
OU	Operable Unit

ABBREVIATIONS AND SYMBOLS (CONTINUED)

PAH	polycyclic aromatic hydrocarbon
Pb	lead
PCB	polychlorinated biphenyl
PFT	Paint Filter Test
pH	negative logarithm of hydrogen ion concentration
PIES	Pollution Prevention Information Exchange System
POTW	publicly-owned treatment works
ppb	part(s) per billion
ppm	part(s) per million
PRP	potentially responsible party
PSD	Prevention of Significant Deterioration
QA/QC	Quality Assurance/Quality Control
QAPP	Quality Assurance Project Plan
3Rs	recovery, reuse, and recycle
RAAS	Remedial Action Assessment System
RCRA	Resource Conservation and Recovery Act of 1976
RCRIS	Resource Conservation and Recovery Information System
RD/RA	Remedial Design/Remedial Action
RfD	reference dose
RFI	RCRA Facility Investigation
RI	Remedial Investigation
RI/FS	Remedial Investigation/Feasibility Study
RM	Remediation Manager
RMERC	BDAT technology code for retorting or roasting mercury for eventual recovery
ROD	Record of Decision
RP	Responsible Party
RPM	Remedial Project Manager
RREL	Risk Reduction Engineering Laboratory (of the U.S. EPA)
SACM	Superfund Accelerated Cleanup Model
SARA	Superfund Amendments and Reauthorization Act of 1986
SB	soil-bentonite
SCE	sequential chemical extraction
SDWA	Safe Drinking Water Act
Se	selenium
SEM	scanning electron microscopy
SET	Sequential Extraction Test
SITE	Superfund Innovative Technology Evaluation Program
SRS	Separation and Recovery Systems, Inc.
SRT	Subsurface Remediation Technology Database
S/S	solidification/stabilization
STLC	Soluble Threshold Limit Concentration
SW	surface water
TCE	trichloroethylene
TCLP	Toxicity Characteristic Leaching Procedure
TDS	total dissolved solids
TIO	Technology Innovation Office (U.S. EPA)
TM	TerraMet
TOC	total organic carbon
TPH, tph	ton(s) per hour
TPY, tpy	ton(s) per year

ABBREVIATIONS AND SYMBOLS (CONTINUED)

TRD	Technical Resources Document
TSCA	Toxic Substances Control Act
TSD	treatment, storage, and disposal facility (RCRA)
TTLC	Total Threshold Limit Concentration
TWA	Total Waste Analysis
UBK	uptake biokinetic
UCS	unconfined compressive strength
USACE	U.S. Army Corps of Engineers
USATHMA	U.S. Army Toxic and Hazardous Materials Agency
U.S. DOE	United States Department of Energy
U.S. DOT	United States Department of Transportation
U.S. EPA	United States Environmental Protection Agency
UST	underground storage tank
VISITT	Vendor Information System for Innovative Treatment Technologies
VOC	volatile organic compound
VORCE	Volume Reduction/Chemical Extraction
WET	see Cal WET, a leaching test

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Gary Adamkiewicz, EPA Region II
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Harry Compton, EPA ERT
Christopher Corbett, EPA Region III
Jim Cummings, EPA TIO
Anita Cummings, EPA OSW
Steven Donohue, EPA Region III
Hugh Durham, EPA RREL
Patricia Erickson, EPA RREL
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Linda Fiedler, EPA TIO
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Steve Mangion, EPA Region V
John Matthews, EPA RSKERL
Shaun McGarvey, EPA OSW
Greg Mickey, EPA Region V
Fred Micku, EPA Region V
Ross Miller, Air Force Center for Environmental Excellence
Robert Mournighan, EPA Region VII
Donald Oberacker, EPA RREL

Asim Ray, Foster Wheeler Environmental Services, Inc.
Robert Robins, Montana College of Mineral Science and Technology (visiting professor)
Larry Rosengrant, EPA OSW
Seymour Rosenthal, Foster Wheeler Environmental Services, Inc.
David Rosoff, EPA Region II
Tamara Rossi, EPA Region II
Ari Selvakumar, Foster Wheeler Environmental Services, Inc.
Don Sternitzke, Dynamac Corporation
Mary Stinson, EPA RREL
James Stumbar, Foster Wheeler Environmental Services, Inc.
Ronald Turner, EPA RREL
J. Jeffrey van Ee, EPA EMSL-LV
Jeffrey Walker, DOE
Anne Wethington, U.S. Bureau of Mines
Chuck Wilk, EPA Region V
Kenneth Wilkowski, EPA RREL
David Wilson, EPA Region V
George Wolf, Foster Wheeler Environmental Services, Inc.
Andre Zownir, EPA ERT

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SECTION 1

INTRODUCTION

1.1 PURPOSE

This reference document is intended to assist site remediation managers (RMs) to select treatment technologies for contaminated soils, sludges, sediments, and waste deposits at sites where inorganic arsenic (As)[1], cadmium (Cd), chromium (Cr), mercury (Hg), or lead (Pb) are the primary contaminants of concern. These five metals have been addressed because of their toxicity, industrial use, and frequency of occurrence at Comprehensive Environmental Response, Compensation, and Liability Act (CERCLA) sites and in Resource Conservation and Recovery Act (RCRA) hazardous wastes. This document should prove useful to all remediation managers, whether their efforts fall under Federal, State, or private authorities, and whether they are applying standards from RCRA, CERCLA, and/or State programs.

1.2 SCOPE AND LIMITATIONS

This project represents a best effort (subject to the key limitations noted below), to identify, collect, analyze, organize, and consolidate information, data, and pertinent references that a remediation manager would find useful for identifying and selecting remedial alternatives for soils, sediments, sludges, and waste deposits in which the principal contaminants are As, Cd, Cr, Hg, or Pb and selected inorganic compounds of these metals.

It is assumed that the RMs are familiar with appropriate policy issues (RCRA, CERCLA, and state), site characterization, sampling methods, analytical methods, risk assessment, determination of cleanup levels, and health and safety plans. Familiarity is assumed, as appropriate, with the references listed in Appendix H.

It is also assumed that the RMs or available support staff are familiar with widely available references (e.g., CRC Handbook of Chemistry and Physics; Merck Index) from which physical and chemical data for the five metals of interest and their compounds can be obtained.

While this technical resource document consolidates information from the past in an attempt to accelerate and improve decisions in the future, it is recognized that site-specific factors ultimately drive the selection of the remedial alternative for any particular site. The remedial action objectives should be clearly established and cleanup levels designated. It is of particular importance to develop reasonable estimates of the volume, distribution, and physical and chemical composition of each significant contaminant/co-contaminant/medium combination at the site that will require remediation. It is similarly important to clearly define the parameters (e.g., total metal(s) concentration, leachable metals, filtered/unfiltered aqueous metal concentrations), test methods (e.g., Toxicity Characteristic Leaching Procedure or TCLP, Extraction Procedure Toxicity Test or EP Tox, other leaching tests, total waste analysis), and numerical goals that will be employed to measure treatment effectiveness. A risk assessment should consider transport and fate of contaminants using the best methods available including equilibrium and/or transport models where applicable.

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[1] For convenience this document will refer to the metalloid, arsenic, as a metal.

An emphasis was placed on keeping the document relatively brief. Therefore, technology descriptions are presented as brief summaries. Compact data tabulations are used where possible.

Containment and water treatment technologies are primarily addressed by reference, since they are well-described and evaluated in recent, available documents, which are referenced in Section 4.

This technical resource document does not apply to sites where the no action or interim remedies are appropriate. The user should refer to *Guide to Developing Superfund No-Action, Interim Action, and Contingency Remedy RODs* (U.S. EPA, 1991, 9355.3-02FS-3) for more information on these remedies.

To avoid redundancy with existing or forthcoming documents, information collection and coverage of the four specific types of metal-contaminated sites listed below were intentionally limited to cases where innovative technologies have been selected or applied:

- Lead battery recycling sites (EPA/540/2-91/014, *Selection of Control Technologies for Remediation of Lead Battery Recycling Sites*)
- Wood preserving sites (As, Cr) – (EPA/600/R-92/182, *Contaminants and Remedial Options at Wood Preserving Sites*)
- Pesticide sites (As, Hg) – (*Contaminants and Remedial Options at Pesticide Sites, in preparation for U.S. EPA*)
- Mining sites (the U.S. EPA Mine Waste Pilot Project, National Superfund Mine Waste Advisory Group, and U.S. Department of Energy (DOE) Resource Recovery Project, various reports)

In the interests of simplicity, brevity, and limited project resources, this technical reference document does not attempt to systematically address remediation of:

- organometallic compounds
- organic-metal mixtures
- multimetal mixtures

For example, while incineration is noted as a potential pretreatment for an organic-metal mixture, the effects of As, Cd, Cr, Hg, or Pb on the technical and economic feasibility of incineration are not discussed. Another example is that several RCRA Best Demonstrated Available Technologies (BDATs) are cited for multimetal wastes, but there is no discussion on how, in general, to select a remedial technology for a multimetal waste.

No claims are made that this document is completely comprehensive in identifying, collecting, analyzing, or listing all pertinent information or data on remediation of metal-contaminated sites. The types of information collected to support preparation of this document include the following.

- Background information on As, Cd, Cr, Hg, Pb, and associated inorganic compounds regarding mineral origins, processing, uses, common matrices, chemical forms, behavior, transport, fate, and effects.
- Existing remediation performance data, listed in rough order of desirability: (a) full-scale remediation of As-, Cd-, Cr-, Hg-, and Pb-contaminated sites; (b) technology demonstrations on As-, Cd-, Cr-, Hg-, or Pb-contaminated sites under the EPA Superfund Innovative Technology Evaluation Program (SITE); (c) RCRA As-, Cd-, Cr-, Hg-, and Pb-bearing hazardous wastes for which BDATs have been established; (d) waste applicability/capacity information for treatment technologies as described in technology guides and the EPA Vendor

Inventory of Superfund Innovative Treatment Technologies (VISITT) database; (e) feedstock specification information for primary or secondary smelting or recycle/re-use markets; (f) Records of Decision (RODs) and corresponding summaries for As-, Cd-, Cr-, Hg-, and Pb-contaminated sites; (g) Treatability test data on As-, Cd-, Cr-, Hg-, and Pb-contaminated matrices where the results are well-documented and in an accessible form (e.g., Alternative Treatment Technology Information Center [ATTIC] and the Risk Reduction Engineering Laboratory (RREL), treatability database; (h) Superfund National Priority List (NPL) sites where As-, Cd-, Cr-, Hg-, or Pb-contaminated media are a primary concern and remedial options are or will be under evaluation.

1.3 ORGANIZATION

Remedial Options and the appendices cited therein form the heart of this reference document. This section begins with a general discussion of the key applicable or relevant and appropriate regulations that influence cleanup goals. Soil and groundwater action levels and risk goals are tabulated for 24 metal-contaminated sites. TCLP limits for metals in selected metal-bearing RCRA characteristic hazardous wastes are also tabulated.

Most of Section 4 addresses the immobilization, and separation/concentration technologies that are potentially applicable for remediating metal-contaminated solids, with the main emphasis on soils. Each technology is addressed in a similar manner.

- A technology description is provided, then a discussion of typical treatment trains; next a discussion of the applicability of the technology to various wastes, with specific reference to the five metals of interest when applicable information is available.
- The status (e.g., bench-, pilot-, full-scale; applications to Superfund remediation) and performance of the technologies are also discussed and, if sufficient examples exist, tabulated.
- Cost factors and costs are also discussed with cost estimates often being drawn from applicable SITE program Applications Analysis Reports.
- Finally, data needs for assessing the applicability of each type of technology are tabulated.

The subsection on immobilization addresses solidification/stabilization (S/S) (cement-based and polymer microencapsulation) and vitrification (in situ and ex situ) technologies. Containment technologies (capping and vertical and horizontal barriers) are noted, but only addressed by reference since: (1) the type of metal contaminant is not a strong influence on containment system selection, and (2) there is a recent, readily available EPA document, *U.S. EPA Handbook: Stabilization Technologies for RCRA Corrective Actions* (EPA 625/6-91/026), that already addresses the topic at the desired level.

Separation/concentration technologies are subdivided into two categories:

- Technologies applicable for excavated solids:
  - Physical separation technologies [i.e., screening, classification, gravity separation, magnetic separation, and flotation]
  - Soil washing technologies [i.e., extraction via water, solvents, or solutions containing surfactants, chelating agents, acids, or bases]

  - Pyrometallurgical separation technologies (i.e., Waelz kiln, flame reactor, molten metal bath, secondary lead smelting via reverberatory and blast furnaces, submerged arc furnace, and mercury roasting and retorting)

- Technologies applied in situ (i.e., soil flushing and electrokinetics).

Water treatment options are very briefly discussed, and a summary table is provided. As with containment options, limited coverage is provided due to the availability of other recent, available EPA documents that address the topic in a suitable manner.

Table 1-1 is a general summary of the technology types which are applicable for remediation of metal-contaminated sites.

TABLE 1-1. REMEDIAL TECHNOLOGIES APPLICABLE TO METAL-CONTAMINATED SITES

- No Action
- Excavation and Off-Site Disposal
- Containment
  - Capping
  - Vertical Barriers
  - Horizontal Barriers
- Solidification/Stabilization (in situ or ex situ)
  - Cement-Based Stabilization
  - Polymer Microencapsulation
- Vitrification (in situ or ex situ)
- Chemical Treatment Technologies (only addressed as a pretreatment)
  - Oxidation
  - Reduction
  - Neutralization
- Separation/Concentration Treatment Technologies (ex situ)
  - Physical Separation/Concentration Treatment Technologies
    - Screening
    - Gravity Separation
    - Floatation
  - Pyrometallurgical Separation
  - Soil Washing
- Separation/Concentration Treatment Technologies (in situ)
  - Soil Flushing
  - Electrokinetic Treatment

Section 4, Remedial Options, is complemented by a number of key appendices, including the following.

- Appendix A presents several stability region diagrams which illustrates the effects of oxidizing potential and pH on the stability of metal compounds.

- Appendix B summarizes 67 technologies applicable to metal-contaminated media that are undergoing evaluation in the SITE Program.

- Appendix C summarizes 39 innovative metal-contaminated technologies from 9 technology categories. This information was excerpted from EPA's VISITT database version 3.0.
- Appendix D lists and briefly describes more than 40 selected metal-contaminated NPL sites.
- Appendix E summarizes BDAT for 60 RCRA hazardous wastes that contain As, Cd, Cr, Hg, and Pb.
- Appendix F supplements the separation/concentration technology portions of Section 4 by providing a review of metal recycling options for metal-contaminated wastes from CERCLA sites. The appendix includes a matrix that matches 37 specific recyclers to 11 lead-bearing materials, 5 mercury-bearing materials, and 16 RCRA metal-bearing hazardous wastes. A list of waste exchanges is also provided.
- Appendix G summarizes the technology types addressed in the document versus 7 of the EPA evaluation criteria employed during selection of Superfund remedial alternatives.
- Appendix H provides a list of key documents, databases, experts, and sources of technical support relevant to remediation of As-, Cd-, Cr-, Hg-, and Pb-contaminated sites.
- Appendix I supplements the cost estimation discussions in Section 4 by providing a description and example applications of EPA's Cost of Remedial Actions (CORA) model. CORA contains cost modules for a variety of remedial options including caps, slurry walls, surface water diversion, soil excavation, sediment excavation and dredging, pumping, soil flushing, ion exchange, off-site RCRA treatment, solidification, offsite RCRA landfill, discharge to publicly-owned treatment works (POTW), and offsite transportation.
- Appendix J summarizes general information on the identification and determination of potential applicable or relevant and appropriate requirements (ARARs) for remedial actions at Superfund metal-contaminated sites.
- Appendix K is a glossary.

Section 2 briefly identifies typical mineral origins, industrial uses, and Superfund matrices of inorganic As, Cd, Cr, Hg, and Pb.

Section 3 addresses possible chemical forms for the five metals under various conditions. It is noted in Section 3 that solubility diagrams and Eh-pH diagrams provide useful summaries of aqueous solution chemistry (e.g., oxidation/ reduction reactions, stability of mobile phases, and hydrolysis of different metals). Sample stability diagrams appear in Appendix A and some applicable computer models are also cited.

Also described in Section 3 are typical environmental transport, partitioning, and transformation phenomena for the five metals in air, soil and sediment, and surface water and groundwater. Factors influencing transport, partitioning, and transformation that are discussed individually or in combination include: airborne transport and subsequent deposition of particulates; interaction of selected stack emissions with natural and anthropogenic compounds prior to deposition in soil; formation of selected volatile compounds; effects of pH, oxidation reduction potential, and valence on aqueous solubility; precipitation; adsorption; ion exchange; complexation with insoluble or soluble soil organic matter; bioconcentration; biomagnification; and biotransformation. Reaction kinetics are discussed semiquantitatively for several cases. Qualitative relative mobility rankings are provided from experimental data for As, Cd, Cr, Pb, and Hg in 11 soil types under anaerobic conditions.

Section 3 also includes a brief overview of the human and environmental toxicity of the five metals and some of their compounds. The topics addressed include: target organs, exposure pathways, ecological effects, reference doses, cancer potency slopes, EPA drinking water limits, OSHA work place air limits, and a very brief discussion of the Uptake Biokinetic model for estimating blood lead levels based on various lead sources. Key references and sources for additional details or information updates are provided.

1.4 REFERENCES

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SECTION 2

ORIGINS, USES, AND MATRICES OF SELECTED CONTAMINANTS AT METAL-CONTAMINATED SITES

This section describes process sources for contaminants, historical trends, and possible chemical and physical conditions for contaminants and waste forms at metal-contaminated sites. This description of typical site and contaminant conditions gives the remedial project manager (RPM) a general framework of understanding for the types of materials requiring treatment at metal-contaminated sites. Due to the diversity of such sites, the information is presented as general surveys indicating the range of conditions that may be encountered.

2.1 ORIGIN AND MAJOR INDUSTRIAL USES OF ARSENIC, CADMIUM, CHROMIUM, LEAD, AND MERCURY

This section outlines the principal industrial applications of the metals discussed in this document. The brief outline for each metal discusses the main industrial uses and the chemical forms that are most likely to be encountered at a particular industrial site. More detail on metal processing and use can be found in standard references such as the *Kirk-Othmer Encyclopedia of Chemical Technology* (Kroschwitz and Howe-Grant, 1991), Metal Statistics (Espinosa, 1993), various U.S. Bureau of Mines (BOM) publications, and the BOM online database (see Appendix H, Subsection H.3.11).

2.1.1 Arsenic

Arsenic (chemical symbol As) is a semi-metallic element or metalloid. For convenience, this report will refer to arsenic as a metal. Arsenic has several allotropic forms. The most stable allotrope is a silver-gray, brittle, crystalline solid that tarnishes in air. Arsenic compounds, mainly As_2O_3, can be recovered as a by-product of processing complex ores mined mainly for copper, lead, zinc, gold, and silver. Arsenic occurs in a wide variety of mineral forms. Worldwide the main commercial ore is arsenopyrite ($FeAsS_4$), but much of the former U.S. production involved copper/arsenic ores such as enargite (Cu_3AsS_4) and tennantite ($(Cu,Fe)_{12}As_4S_{13}$). Because arsenic is a by-product, its supply depends primarily on the demand for the main metals in the ores. Arsenic use in 1992 was 23,900 metric tons, of which 67% was for production of the wood-treatment chemical chromated copper arsenate (CCA). Agricultural use was 23% of the total in 1992, but will be declining due to cancellation of approval for use of arsenic chemicals as cotton leaf desiccants (58 FR 26975). All arsenic consumed in the United States in 1991 was derived from imported sources. Arsenic is regarded as a zero-value impurity by most U.S. mine and smelter operators. As a result, operators are likely to avoid ores containing arsenic when possible (Loebenstein, 1992).

2.1.2 Cadmium

Cadmium (chemical symbol Cd) is a bluish-white, soft, ductile metal. Pure cadmium compounds rarely are found in nature, although occurrences of greenockite (CdS) and otavite ($CdCO_3$) are known. The main sources of cadmium are sulfide ores of lead, zinc, and copper. Cadmium is recovered as a by-product when these ores are processed. Because cadmium is produced as a by-product of sulfide ore refining, its production rate is more closely coupled to zinc demand than to cadmium demand. Cadmium use varied from 3,107 to 4,096 metric tons between 1988 and 1992. The peak use was 4,096 metric tons in 1989. The estimated apparent consumption in 1992 was 3,400 metric tons. About half of the cadmium used goes for production of nickel-cadmium batteries. Other uses include plating, pigments, plastics, and alloys (U.S. Bureau of Mines, 1993).

2.1.3 Chromium

Chromium (chemical symbol Cr), a lustrous, silver-gray metal, is one of the less common elements in the earth's crust and occurs only in compounds. The chief commercial source of chrome is the mineral chromite ($FeCr_2O_4$). Chromium is mined as a primary product and is not recovered as a by-product of any other mining operation. There are no chromite ore reserves, nor is there primary production of chromite in the United States.

Total apparent chromium consumption ranged from 366,000 to 537,000 metric tons of contained chromium between 1988 and 1992. Peak consumption of 537,000 metric tons occurred in 1988. The estimated consumption for 1992 was 435,000 metric tons of contained chromium. The consumption figures include primary production and secondary sources from recycling. Chromium contained in purchased stainless steel is estimated to account for about 26% of the consumption of recycled chromium in 1992 (U.S. Bureau of Mines, 1991).

2.1.4 Lead

Lead (chemical symbol Pb) is a bluish-white, silvery or gray metal that is highly lustrous when freshly cut, but tarnishes when exposed to air. It is very soft and malleable, has a high density (11.35 g cm^{-3}) and low melting point (327.4°C), and can be cast, rolled, and extruded. The estimated consumption of lead in 1992 was 1,220,000 metric tons. Of this amount, 80% was used in lead-acid batteries. About 760,000 metric tons of lead was recovered from scrap batteries in 1992.

2.1.5 Mercury

Mercury (chemical symbol Hg) is a silvery liquid metal. The primary source of mercury is the sulfide ore, cinnabar (HgS). In a few cases, mercury occurs as the principal ore product. Mercury is more commonly obtained as the by-product of processing complex ores that contain mixed sulfides, oxides, and chloride minerals, which are usually associated with base and precious metals, particularly gold. Native or metallic mercury is found in very small quantities in some ore sites.

Mercury for United States use came from domestic mines, sales of surplus from government stocks, imports, and waste recovery. Mercury was produced as the main product of the McDermitt Mine and as a by-product of nine gold mines in Nevada, California, and Utah (U.S. Bureau of Mines, 1993). The McDermitt Mine is now closed. Market expectations indicate a continuing decline in mercury use and increased reliance on recycled mercury (Espinosa, 1993).

The total use of mercury in 1992 was 621 metric tons. The main users were mercury-cell chloralkali plants. The use of mercury is expected to decline and the supply of recycled mercury is expected to increase. Smaller amounts of mercury are produced when secondary sources are reprocessed. In 1992, commercial secondary mercury reprocessors produced 176 metric tons of mercury (U.S. Bureau of Mines, 1993). Common secondary mercury sources are spent batteries, mercury vapor and fluorescent lamps, switches, dental amalgams, measuring devices, control instruments, and laboratory and electrolytic refining wastes. The secondary processors typically use retorting to recover mercury from compounds and distillation to purify contaminated liquid mercury metal.

2.2 OVERVIEW OF SOURCES OF CONTAMINANTS AT METAL-CONTAMINATED SITES

Wastes at CERCLA sites are frequently heterogeneous on a macro and micro scale. The contaminant concentration and the physical and chemical form of the contaminant and matrix usually are complex and variable. Waste disposal sites collect a diverse variety of waste types causing concentration profiles to vary by orders of magnitude through a pit or pile. Limited volumes of high-concentration "hot spots" may develop due to variations in the historical waste disposal patterns or local transport mechanisms.

Similar radical variations frequently occur on the particle-size scale as well. The waste often consists of a physical mixture of very different solids, for example, paint chips in spent abrasive. These variations in contaminant concentration and matrix type require that the design of sampling for analysis and treatability studies be done with caution. Due to the importance of matrix effects, treatability studies should be performed on actual site material rather than on synthetic materials whenever possible.

2.2.1 Stack Emissions

Stack emissions are point source emissions from stacks, vents, ducts, pipes, or other confined air, gas, or vapor streams. Air releases from pollution control equipment typically are considered stack emissions. Metal contaminants will be present in gas streams as fine particulates. Solids with small particle size may be entrained in a gas stream during material handling, mixing, or size reduction. In high-temperature processing, some metals (particularly arsenic, cadmium, lead, and mercury) can volatilize. Unless a reducing atmosphere is maintained, the metal will quickly convert to an oxide and condense as a very fine particulate typically called a "fume" or a "condensed fume."

Offgas treatment may be applied to collect the metal-bearing particulates. Depending on the process and application, either a wet scrubbing system or a dry filtration system may be used to collect the particulates. Wet scrubbing produces a sludge waste, whereas filtration results in dry powder. These solid waste material types are discussed below.

At many older plants, offgas particulate removal systems did not work well or were not used. Even if offgas treatment systems are used, particulate removal is never complete. Particulates escaping a plant's point source emission release locations will be distributed by natural air currents until they settle out due to gravity. In many cases tall stacks are used to obtain dilution. Airflow then distributes the metal contaminants over a wide area.

The resulting contaminant deposition will distribute contaminants generally downwind from the plant. The pattern of contaminant deposition will depend on many site-specific factors such as offgas flow and composition, wind direction and speed, and duration of operation. The concentration of metals in the offgas typically is low, but in some cases plant operation over many years allows a buildup of measurable contaminant levels. For example, one operable unit of the Superfund site at Palmerton, Pennsylvania, is a mountainside contaminated with oxides of cadmium, lead, and zinc due to operation of a smelter.

2.2.2 Fugitive Emissions

Fugitive emissions are air emissions not covered by the point source stack emissions described above. Some examples of fugitive emissions include:

- Dust from loading, unloading, and equipment operation
- Airborne losses due to spills
- Dust carried by wind from material storage areas or waste piles
- Releases from general building ventilation

As with the stack emissions, the metal contaminants typically leave the source as solid particulates or very quickly convert to particulate form.

In general, the contaminant concentration in the fugitive emission sources will be lower than in the stack emissions, but the emissions will occur near the ground. As a result, the distribution area usually will be smaller. As with stack emissions, the actual concentrations encountered depend on site-specific conditions.

2.2.3 Process Solid-Phase Waste Materials

Industrial processes may result in a variety of solid metal-bearing waste materials, including slags, fumes, mold sand, fly ash, abrasive wastes, spent catalysts, spent activated carbon, and refractory bricks (Zimmerman and Coles, 1992). These process solids may be deposited above ground as waste piles or below ground in landfills. Solid-phase wastes can be dispersed by well-intended but poorly controlled reuse projects. For example, many slags can serve as good quality materials for construction applications such as road subgrade, fill material, or daily landfill cover. However, slags containing leachable levels of cadmium, lead, or other metals have been used for construction fill and have created problems. Similarly, metal-contaminated sludge has been spread as fertilizer (50 FR 658, January 4, 1985).

2.2.3.1 Waste Piles

Large volumes of dry solid-waste materials frequently are accumulated in waste piles. Because the waste piles are exposed to weathering, they can be sources of contamination to the surrounding soil or groundwater. In addition, waste piles can be exposed to natural disasters or accidents causing further dispersion. For example, a fire at a material pile belonging to Frit Industries in Walnut Ridge, Arkansas, resulted in contamination to soil and water by runoff of water used to fight the fire (50 FR 658, January 4, 1985).

Slags--

Slag is a fused solid consisting mainly of inorganic oxides of silicon, iron, and calcium with metallic impurities. Slag is a typical waste product from pyrometallurgical metal processing. The slag composition depends on the feed material source and the process used. Slags generally contain silica (SiO_2) as the main constituent along with fluxing salts (e.g., calcium and magnesium) and metals from the ore.

Density, porosity, and leach resistance are the main properties considered in evaluating slag as a contaminated matrix. These properties vary depending on the method of producing the slag. The form of slag produced depends on the conditions used for cooling. Testing has indicated that faster slag cooling is important to maximize formation of vitreous materials which reduces the mobility of metals.

Other Metal-Bearing Wastes--

Other metal-bearing wastes include fumes, foundry sand, fly ash, abrasives, catalysts, spent activated carbon, refractory bricks, etc. Fumes are very fine particulates produced during high-temperature metal processing. Volatile metals or metal oxides evaporate and recondense to form the fume. One common example is condensed silica fume, a fine particulate consisting of over 90% silica. Condensed silica fume is a by-product of ferroalloy production. Metal impurities may impart a hazardous waste characteristic. The fume is an artificial pozzolan with a very high activity due to its small particle size and amorphous structure. Volatile metals such as cadmium and zinc also are prone to fume formation. The fine-particle fumes are difficult to transfer by conventional materials-handling techniques due to moisture absorption and poor flow properties (Popovic et al., 1991).

Foundries use sand to make molds and cores to contain and shape metal during casting. The sand grains are held together with additives called "binders." Mold-making techniques may use sand mixed with a small amount of clay and water or more complex binder systems such as silicates or organic resins such as phenolic-urethane polymers.

Fly ash is fine particulate carried in the offgas exiting processes such as smelting or coal combustion. Fly ash particles form in a high-temperature gas stream. At the typical combustion or processing temperature of about 1600°C (2900°F), the ash material is a molten sphere. As the particles cool and solidify, they retain a generally spherical shape. The particulate is collected by baghouses, electrostatic precipitators, or similar offgas cleaning equipment. The particulate is mainly glassy, spherical silicate and aluminate material with particle sizes in the range of 1 to 150 micrometers (μm) (Gera et al., 1991). The fine particulate may be removed from the offgas cleaning equipment as either a dry powder or a water slurry and then be sent to a storage pile for subsequent disposal or recycling.

Abrasives are powdered, granular, or solid materials used to grind, smooth, cut, or polish other substances. The abrasive wears down the surface of materials to alter their shape or give the desired finish. Sand, ground quartz, pumice, and corundum are commonly used natural abrasives. Synthetic abrasives such as Carborundum™ (silicon carbide, SiC) and alumina (aluminum oxide, Al_2O_3) are prepared for special applications. Abrasives can become contaminated with metals during use. For example, chips from a paint with lead or chromate pigments may cause the spent abrasive to have a hazardous waste characteristic.

Catalysts for industrial process use typically are a ceramic support carrying a small quantity of metal catalyst such as a chromium, nickel, or platinum group metal. The supporting ceramic usually is a sphere of controlled particle size consisting mainly of alumina (Al_2O_3) and silica (SiO_2). In use, the catalyst becomes fouled with reactants or reaction products. Catalyst activity often can be recouped by thermal regeneration, but some of the particles break during the regeneration process. Once the catalyst particles become too small to be useful, they can become a waste disposal problem.

Spent activated carbon results from a variety of wastewater treatment or offgas cleaning operations. Activated carbon adsorption may be applied to offgas cleanup or to removal of metals from aqueous streams. The carbon may become a characteristic hazardous waste due to sorbed contaminants (Dungan, 1992).

Refractory bricks are high-performance ceramic materials used to line high-temperature processing equipment. Refractory bricks are made from chromite or similar chromium oxide materials. The bricks deteriorate in use and are replaced periodically during furnace maintenance (Martin et al., 1987). Many refractory bricks contain percentage levels of chromium and can exhibit the D007 chromium toxicity hazard characteristic (see Appendix E). The bricks also may become contaminated by process materials during use.

Metals in Polymer Matrices--

Metals, metal salts, and organometallic compounds are incorporated in polymer matrices to act as fillers, improve mechanical properties, or provide colors. For example, organolead compounds are used in wire and cable insulation; cadmium is used in plastics; and various lead, cadmium, and chromate pigments are used in paints and plastics.

Industrial maintenance or metals recovery operations can generate significant volumes of metal-bearing polymer waste. Examples are recovery of copper or aluminum from wire, recovery of steel from automobiles, and paint removal. The polymer usually is removed by shredding or abrasive blasting and thus is left as a finely divided particulate. The residue from shredding is a finely divided polymer called "fluff." The fluff contains metals as a constituent as well as metal particulate contaminants from the substrate. Paint removal debris typically will be produced as an abrasive blasting medium contaminated with the paint debris containing metal pigments, substrate metal, and metal oxide particulate.

2.2.3.2 Landfills

Metal-contaminated wastes are frequently deposited in landfills. Landfills are subgrade waste-holding or disposal facilities. Landfill designs range from a simple pit to a complex lined and capped disposal facility. The landfill may contain process solid waste or sludges or other sources of metal contaminants. Infiltrating surface water or migrating groundwater can pass through the waste material in landfills, resulting in contaminated leachate. Surrounding soils may become contaminated due to leaching from the landfill. Uncontrolled landfills can also release contaminants via wind and surface erosion.

2.2.4 Sludges

A general definition of sludge is a thick, water-based suspension of solid particles. Sludges may include metal hydroxides, carbonaceous materials, silicates, and other industrial by-products formed into a semisolid mass. RCRA and the implementing regulations take a somewhat more specific approach, defining sludges as residues from air or wastewater treatment or other pollution control operations (50 FR 618, January 4, 1985).

Many industrial metal-contaminated sludges are hydroxide or sulfide precipitates from treatment of wastewater. In addition to the chemicals added to cause precipitation and the precipitated contaminants, the sludge may contain flocculants and filter aid. Depending on the source and age of the sludge, the waste matrix composition will range from uniform to heterogeneous.

Hydroxide or sulfide sludges derived from well-controlled treatment of a uniform wastestream will have uniform and predictable matrix characteristics. Wastewater treatment sludges from inorganic pigment manufacture or plating operations are common industrial examples of such sludges. Sludges containing high concentrations of a single metal also can result from grinding or offgas scrubbing processes. A clean, well-controlled sludge that is contaminated with one or two metals and/or has a high metal concentration is a good candidate for recycling.

Sludge pits at CERCLA sites typically represent the other extreme. At such sites, waste treatment sludges were discharged to holding pits. As the wastes weather in the pits, hydroxides convert to carbonates and various hydration reactions occur. Further, the pits become a repository for all manner of facility wastes including pallets, bricks, broken tools and equipment, and drummed wastes. Additional miscellaneous wastes may enter the pit from illegal offsite sources.

Many of the CERCLA waste pits have been abandoned for some period with little or no access control. Abandoned waste sites are an inviting location for disposal of wastes by parties not involved in known use of the site. This sort of "midnight waste disposal" is suspected to have occurred at the King of Prussia CERCLA site, Winslow Township, NJ, for example. Before any attempt at recycling, wastes from old sludge pits almost certainly will require significant pretreatment or, at a minimum, sorting, screening, and sizing.

2.2.5 Soils

Soils can become contaminated with metals as a result of direct contact with plant waste discharges, fugitive emissions, or leachate from waste piles; landfills; or sludge deposits. Soil consists of weathered mineral grains and organic materials in varying proportions. Soils typically are heterogeneous and may be stratified due to historical variations during the soil formation process. Soil layers form as a result of interaction between the soil and groundwater, atmosphere, and vegetation. The properties of upper layers are particularly affected by biological activity of plants and microorganisms. As a result, the surface soil properties are strongly influenced by soil chemistry, moisture content, and climatic conditions.

The wide variations in natural soil properties and contaminant levels encountered in site remediation cannot be overemphasized. Soil and contaminant conditions certainly will vary from site to site. Conditions may also vary widely within one site. The process or equipment selected to handle contaminated soils should typically be able to accept wide variations in soil conditions and contaminant levels.

Many systems are available for classifying soil type and constituents. Most of these classifications include particle size as the primary physical parameter. Typical classifications, in order of decreasing size, are: gravel, sand, silt, and clay.

The organic content of soil can vary from <1% in dry, sandy soils to >20%. The chemistry of the organic portion of soils is complex. The soil organic content will consist of high-molecular-weight humic materials and lower-molecular-weight organic acids and bases. The high-molecular-weight organic materials in soil have low water solubility and high affinity for metals and account for most of the metal immobilization due to soil organic matter. These high-molecular-weight organic acids immobilize metals by complexation and chelation mainly due to acidic sites. The lower-molecular-weight organics tend to mobilize metals by forming soluble complexes with metals (Czupyrna et al., 1989).

Other characteristics that help identify soil type and behavior include structure, color, density, type, and amount of organic and inorganic colloidal materials. Typical engineering properties, such as density and Atterberg limits, will indicate the handling properties of the soil. The solubility of metals in soil is controlled by factors such as pH, Eh, the ion exchange capacity, and complexing and chelation effects of organic matter. Measurement methods and the significance of each of these factors have been described in several documents (Bodek et al., 1988; Cameron, 1992; Sims et al., 1984).

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SECTION 3

CONTAMINANT BEHAVIOR, FATE, TRANSPORT, AND TOXICITY

At every metal-contaminated site, testing and analysis should be performed to measure the concentrations of metals present, to determine the species and physical form, and to determine the extent of metals contamination. It is imperative, however, that the background concentration of the metals also be analyzed. It often is assumed that all metals measured at a site are contaminants, but in reality, high concentrations of many metals may be native to the area. As shown in Table 3-1, the common ranges of As, Cd, Cr, Pb, and Hg in typical soils are 1 to 50, 0.01 to 0.70, 1 to 1,000, 2 to 200, and 0.01 to 0.3 ppm, respectively. The typical background concentrations for these metals are 5, 0.06, 100, 10, and 0.03 ppm, respectively (U.S. EPA, 1987, EPA/540/P-87/001B).

TABLE 3-1. REPRESENTATIVE METAL CONTENT TYPICAL OF SOILS

Element	Common range for soils (ppm)	Selected average for soils (ppm)
Arsenic (As)	1 – 50	5
Cadmium (Cd)	0.01 – 0.70	0.06
Chromium (Cr)	1 – 1,000	100
Lead (Pb)	2 – 200	10
Mercury (Hg)	0.01 – 0.3	0.03
Barium (Ba)	100 – 3,000	430
Boron (B)	2 – 100	10
Copper (Cu)	2 – 100	30
Manganese (Mn)	20 – 3,000	600
Nickel (Ni)	5 – 500	40
Selenium (Se)	0.1 – 2	0.3
Silver (Ag)	0.01 – 5	0.05
Tin (Sn)	2 – 200	10
Zinc (Zn)	10 – 300	50

Adapted from U.S. EPA, 1987, EPA/540/P-87/001B.
Important sources for information on behavior, fate, and transport include Bodek et al. (1988); Dragun (1988); McLean and Bledsoe (1992); and U.S. Department of Health and Human Services (1991a, 1991b, 1991c, 1991d, and 1992).

3.1 CHEMICAL FORMS AND SPECIATIONS

This section describes possible chemical forms for metal contaminants under typical soil and waste matrix conditions based on the background information presented in Section 2 and on geochemical principles. Conditions of compounds of pure metals are emphasized. The effects of mixed metal and metal/organic combinations are discussed when applicable.

Solubility and Eh-pH diagrams provide a useful summary of aqueous solution chemistry for a given system and provide a framework for evaluating oxidation/reduction reactions, stability of mobile phases, and hydrolysis for different metals. Example diagrams are provided in Appendix A to illustrate the potential for these diagrams. Computer models such as STABCAL (Huang, 1993), MINTEQA2 (U.S. EPA, 1991, EPA/600/3-91/021), and Outokumpu (Roine, 1993), are available to allow calculation of the diagrams.

3.1.1 Arsenic

In most arsenic-contaminated sites, arsenic is present as As_2O_3 or as arsenic species leached from As_2O_3, oxidized to As(V), and then sorbed onto iron-bearing minerals in the soil. Arsenic also may be present as organometallic forms, such as methylarsenic acid ($H_2AsO_3CH_3$) and dimethylarsenic acid ($(CH_3)_2AsO_2H$), which are active ingredients in many pesticides), as well as arsine (AsH_3) and its methyl derivatives (dimethylarsine ($HAs(CH_3)_2$) and trimethylarsine ($As(CH_3)_3$)). These arsenic forms illustrate the various oxidation states that arsenic commonly exhibits (-III, 0, III, and V), and the resulting complexity of its chemistry in the environment.

The chemistry of As(V) resembles that of P(V). As(V) exhibits anionic behavior in the presence of water and can form insoluble metal arsenates. In aerobic environments, H_3AsO_4 predominates at pH <2 and is replaced by $H_2AsO_4^-$, $HAsO_4^{2-}$, and AsO_4^{3-} as pH increases to about 2, 7, and 11.5 respectively. Under mildly reduced conditions, H_3AsO_3 is a predominant species at low pH, but is replaced by $H_2AsO_3^-$, $HAsO_3^{2-}$, and AsO_3^{3-} as pH increases. Under still more reduced conditions and in the presence of sulfide, As_2S_3 can form. As_2S_3 is a low-solubility, stable solid. $HAsS_2$ and AsS_2^{2-} are thermodynamically unstable with respect to As_2S_3 (Wagemann, 1978). Under extreme reducing conditions, elemental arsenic and arsine can occur. Methylation of arsenic can result in highly volatile methylated arsine derivatives.

Because it forms anions in solution, arsenic does not form complexes with simple anions such as Cl^- and SO_4^{2-}. Anionic arsenic, such as arsenate (AsO_4^{3-}) and arsenite (AsO_3^{3-}), behaves like a ligand and precipitates with many metal cations (Bodek et al., 1988). As(V) is less mobile (and less toxic) than As(III). (This phenomenon is just the opposite of Cr, where Cr(VI) is more mobile and toxic than Cr(III).) Calcium arsenate ($Ca_3(AsO_4)_2$) is the most stable metal arsenate in well-oxidized and alkaline environments, but it is unstable in acidic environments. Even under initially oxidizing and alkaline conditions, absorption of CO_2 from the air will result in formation of $CaCO_3$. Sodium often is available, such that the mobile compound Na_3AsO_4 can form. The slightly less stable manganese arsenate ($Mn_2(AsO_4)_2$) forms in both acidic and alkaline environments. However, its mobility increases in well-oxygenated systems (Sadiq et al., 1983). Under acidic and moderately reducing conditions (0 to 100 mV), arsenic will coprecipitate with or adsorb onto iron oxyhydroxides [as As(V)] (Masscheleyn et al., 1991). These species are immobile as long as acidic and reducing conditions are maintained. Mobility increases with decreasing Fe/As ratio and increasing pH. For example, the solubility varies from a minimum of <0.05 mg/L at an Fe:As mole ratio of 16:1 to a maximum of 510 mg/L with equal molar amounts of Fe and As (Krause and Ettel, 1989). The arsenic ferrihydride species has been suggested as a disposal medium for arsenic, although there is some debate concerning its solubility (Robins, 1981; Krause and Ettel, 1989). Lead arsenate ($Pb_3(AsO_4)_2$) also has been suggested as a possible solid in natural environments, but it has not been established whether the mechanism is precipitation or sorption onto solid surfaces (Hess and Blancher, 1977).

Arsenite also is present in aqueous systems under reduced conditions. It has a strong affinity for sulfur and readily adsorbs or coprecipitates with metal sulfides (Ferguson and Gavis, 1972). However, the adsorption of arsenite onto clays, carbonates, or other hydroxides has not been investigated.

Arsenic forms bonds with organic sulfur, nitrogen, and carbon. As(III) reacts with sulfur and sulfhydryl groups, such as cystine, organic dithios, proteins, and enzymes, but does not react with amine groups or organic compounds with reduced nitrogen constituents. On the contrary, As(V) reacts with reduced nitrogen groups, such as amines, but not with sulfhydryl groups. Arsenic (both III and V) forms organo-arsenicals with carbon. The complexation of arsenic by dissolved organic matter in natural environments prevents sorption and coprecipitation with solid-phase organics and inorganics, thus increasing the mobility of arsenic in aquatic systems and in the soil.

3.1.2 Cadmium

Plating operations, nickel-cadmium battery manufacturing, pigment manufacturing and applications and disposal of cadmium-containing wastes are the principal sources of cadmium contamination at metal-contaminated sites. Cadmium exists as Cd^{2+} ion, $Cd\text{-}CN^-$ complexes, or $Cd(OH)_2$ sludge at most metal-contaminated sites, depending on pH and treatments that Cd wastes receive before disposal to pits and/or lagoons. At pH <8, cadmium occurs primarily as the dissolved divalent ion, Cd^{2+}, or aqueous sulfate species. As pH increases, cadmium precipitates to form $Cd(OH)_2$ and $CdCO_3$. $CdCO_3$ is significantly less soluble than $Cd(OH)_2$; its solubility increases as dissolved CO_2 concentration increases. Under reduced conditions and in the presence of sulfide, a stable cadmium compound, CdS, forms. Cadmium also forms precipitates with phosphate, selenite, selenate, arsenate, and chromate; the solubilities of these precipitates vary under different pH and geochemical conditions.

3.1.3 Chromium

At most metal-contaminated sites, chromium is released to land, surface water, and groundwater from electroplating and leather tanning operations, pigment manufacturing and applications, and textile manufacturing, and from disposal of chromium-containing wastes. Chromium usually carries +VI or +III valence. The hexavalent chromium (CrO_4^{2-} and $Cr_2O_7^{2-}$) is the major chromium species used in industry (except tanning), and is more toxic and mobile. The two forms of hexavalent chromium are pH dependent. Chromate ion (CrO_4^{2-}) predominates above pH 6 under oxidizing conditions and $Cr_2O_7^{2-}$predominates at lower pH under moderately reducing conditions. Because of its anionic nature, Cr(VI) precipitates with metal cations, such as Ba^{2+}, Pb^{2+}, and Ag^+. Cr(VI) also complexes with multiple sites on soil surfaces having positively charged sites, the number of which decrease with increasing soil pH. As a result, adsorption of Cr(VI) onto the surface of iron oxide, aluminum oxide, and other soil constituents occurs only at an acidic or neutral pH. The trivalent chromium is less toxic and tends to adsorb onto clays below pH 4. Above pH 5, chromium's immobility is attributed to the formation of $Cr(OH)_3$ solid, and, between pH 4 and 5, to both precipitation and adsorption (Chrotowski et al., 1991). Cr(III) also forms complexes with fluoride, ammonia, cyanide, sulfate, and many soluble organic ligands, all of which may increase the mobility of chromium.

Cr(VI) is reduced to Cr(III) in the presence of ferrous iron, dissolved sulfides, and organic compounds, particularly sulfhydryl groups. The reduction reaction proceeds at a slow rate under ambient pH and temperatures; however, the rate of reaction increases with decreasing soil pH. Cr(III) can be oxidized to Cr(VI) by a large excess of MnO_2; oxidation by oxygen occurs slowly under natural water conditions (Chrotowski et al., 1991).

3.1.4 Lead

Lead (Pb) is released to land, surface water, and groundwater primarily from ferrous and nonferrous metal smelting and processing, secondary metals producing, lead battery manufacturing, and pigment and chemical manufacturing, as well as from the disposal of lead-containing waste. Most of the lead released is in the form of lead metal, lead oxides and hydroxides, and lead-metal oxy-anion complexes. The most common oxidation states for lead are 0 and +II. Pb(II) forms both mononuclear and polynuclear oxides and the corresponding hydrates and hydroxides. However, Pb^{2+} and hydroxy complexes are the most stable species under most conditions. Lead also forms stable complexes with both inorganic (e.g., Cl^-, CO_3^{2-}) and organic (e.g., humic and fulvic acid) ligands present in soils and aquatic systems (Bodek et al., 1988).

Soluble lead also reacts with carbonates, sulfides, sulfates, and phosphates to form low-solubility compounds. At pH values above 6, lead forms lead carbonate (McLean and Bledsoe, 1992). In solutions with high concentrations of sulfide, lead precipitates to form PbS. PbS is the most stable solid in reduced conditions with sulfur (Hem and Durum, 1972). PbS will be converted to lead hydroxide, carbonate, or sulfate when the sulfur is oxidized to sulfate. In the presence of phosphate, stable lead phosphates and lead phosphate chlorides will form (Clever and Johnston, 1990).

3.1.5 Mercury

Mercury is released to the environment primarily from a number of industrial processes including chloralkali manufacturing, copper and zinc smelting operations, paint application, waste oil combustion, geothermal energy plants, municipal waste incineration, chemical manufacturing, ink manufacturing, paper mills, leather tanning, pharmaceutical production, and textile manufacturing, as well as from the disposal of industrial and domestic products (e.g., thermometers, electrical switches, and batteries) as solid wastes in landfills. In a metal-contaminated site, mercury exists in mercuric form (Hg^{2+}), mercurous form (Hg_2^{2+}), elemental form (Hg^0), or alkylated form (e.g., methyl and ethyl mercury). Hg_2^{2+} and Hg^{2+} are more stable under oxidizing conditions. Under mildly reducing conditions, both organically bound mercury and inorganic mercury compounds may be degraded to elemental mercury that can be converted readily to methyl or ethyl mercury by biotic and abiotic processes. Methyl and ethyl mercury are the most toxic forms of mercury. The alkylated mercury compounds are volatile and soluble in water.

Mercury(II) forms relatively strong complexes with Cl^- and CO_3^{2-}. Stumm and Morgan (1981) suggested that the principal dissolved Cl^- complexes are $HgCl_4^{2-}$ in seawater and HgOHCl in fresh water under aerobic conditions. The other Cl^- complexes present under aerobic conditions are $HgCl^+$, $HgCl_2$, $HgCl_3^-$, and $HgCl_4^{2-}$. Mercury(II) also forms complexes with other inorganic ligands such as F^-, Br^-, I^-, SO_4^{2-}, S^{2-}, and PO_4^{3-}. The insoluble HgS is formed under mildly reducing conditions. Mercury(II) forms strong complexes with organic ligands, such as sulfhydryl groups, amino acids, and humic and fulvic acids.

Mercury is very soluble in oxidized aquatic systems. Its solubility is greatly influenced by its strong complexation with inorganic and organic ligands. For example, at a Cl^- concentration of 35,460 mg/L, the solubilities of $Hg(OH)_2$ and HgS increase by factors of 10^5 and 3.6×10^7, respectively. At a Cl^- concentration of only 3.5 mg/L, the solubilities of these two compounds increase by factors of 55 and 408, respectively. The solubilities of HgS, HgO, and $HgCl_2$ also increase in the presence of humic acid (Bodek et al., 1988).

3.2 ENVIRONMENTAL FATE AND TRANSPORT

This subsection describes typical environmental fate and transport mechanisms for metals in contaminated sites. As indicated in the following subsections, the descriptions include transport and partitioning as well as transformation. Metal transformations are described according to environmental media types, including air, soil and sediment, and surface water and groundwater.

Trace levels of As, Cd, Cr, Pb, and Hg may be released into the atmosphere from the off-gas of open-hearth furnaces in steel mills; zinc, cadmium, and lead smelters; and incinerators (Schroeder et al., 1987). The airborne particulates are present mainly as oxides or in the form of chlorides in some incinerator emissions. Significant coagulation and interaction can occur in the atmosphere between emitted species and ambient particles of both natural and artificial origin. The particulate matter eventually will be removed from the atmosphere by wet or dry deposition and will be dispersed to a wide area of soil, causing soil contamination or damage to plants. For example, the zinc smelters at the Palmerton Zinc (OU-1) site in Carbon County, Pennsylvania, emitted large quantities of Zn, Pb, Cd, and SO_2 that led to the defoliation of approximately 2,000 acres on Blue Mountain adjacent to the smelters (U.S. EPA, 1987, EPA/ROD/R03-87/036).

In soil and sediment, metal contaminants are dissolved in the soil solution, adsorbed or ion-exchanged on inorganic soil constituents, complexed with insoluble soil organic matter, and precipitated as pure or mixed solids. Metals in the soil solution are subject to movement with soil water, and may be transported through the vadose zone to groundwater, taken up by plants and aquatic organisms, or volatilized. Unlike organic contaminants, metals cannot be degraded, but some metals such as As, Cr, and Hg can be transformed among various oxidation states, altering their mobility and toxicity. Metal contaminants participate in chemical reactions with the soil solid phase. Immobilization of metals by adsorption, ion exchange, complexation, and precipitation can prevent the movement of metal contaminants to groundwater. Changes in soil conditions, such as degradation of organic matrices and changes in pH, redox potential, or soil solution composition, due to various remediation schemes or to natural weathering processes, also may change metal mobility.

Metal contaminants also may be dispersed to a wide area of soil by well-intended but poorly considered uses, such as using a slag with leachable Pb or Cd as a road covering or fill material. However, it must be noted that spreading slag is not necessarily a bad practice. In fact, all iron and most steel slag now used in construction contains primarily silicate minerals with very low hazardous metal content and near zero leachability.

The qualitative ranking of the relative mobilities of As, Cd, Cr, Pb, Hg, and 6 other metals in the 11 soils listed in Table 3-2 have been ranked to indicate possible mobility of these metals under anaerobic conditions and a pH of 5 (Korte et al., 1976). Of the cationic metals studied, Cu and Pb are the least mobile and Hg(II) is the most mobile (see Figure 3-1). The heavier textured soils with higher pH are effective in attenuating the metals, whereas sandy soils and/or soils with low pH do not retain the metals effectively. For the anionic metals studied, Cr(VI) is the most mobile anion (Figure 3-2). Clay soils containing oxides with low pH are the most effective in retaining the anions. On the contrary, the light-textured soils are the least effective in retaining anions. The relative mobility of nine metals through montmorillonite and kaolinite is:

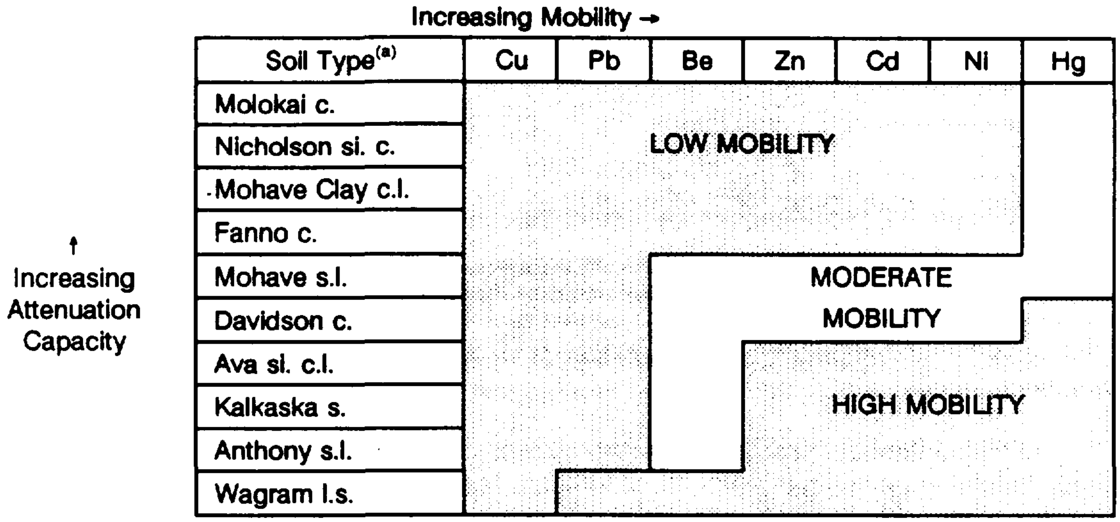
$$Cr(VI) > Se > As(III) > As(V) > Cd > Zn > Pb > Cu > Cr(III)$$

Table 3-2 and Figures 3-1 and 3-2 illustrate the importance of clay minerals in reducing the mobility of cationic metals, the moderate to high mobility of mercury, and the effect of iron minerals in reducing the mobility of metal- and metalloid-bearing anions.

TABLE 3-2. CHARACTERISTICS OF SOIL TYPES

Soil Type	Soil Order	pH	CEC m_{eq}/100 g	Surface area m^2/g	Free Fe oxides %	Clay %	Texture
Wagram	Ultisol	4.2	2	8.0	0.6	4	loamy sand
Ava	Alfisol	4.5	19	61.5	4	31	silty clay loam
Kalkaska	Spodosol	4.7	10	8.9	1.8	5	sand
Davidson	Ultisol	6.2	9	61.3	17	61	clay
Molokai	Oxisol	6.2	14	67.3	23	52	clay
Chalmers	Mollisol	6.6	26	125.6	3.1	35	silty clay loam
Nicholson	Alfisol	6.7	37	120.5	5.6	49	silty clay
Fanno	Alfisol	7.0	33	122.1	3.7	46	clay
Mohave	Aridisol	7.3	10	38.3	1.7	11	sandy loam
Mohave Clay	Aridisol	7.8	12	127.5	2.5	40	clay loam
Anthony	Entisol	7.8	6	19.8	1.8	15	sandy loam

Adapted from Korte et al. (1976) with permission of the authors and of the publisher, Williams & Wilkins.

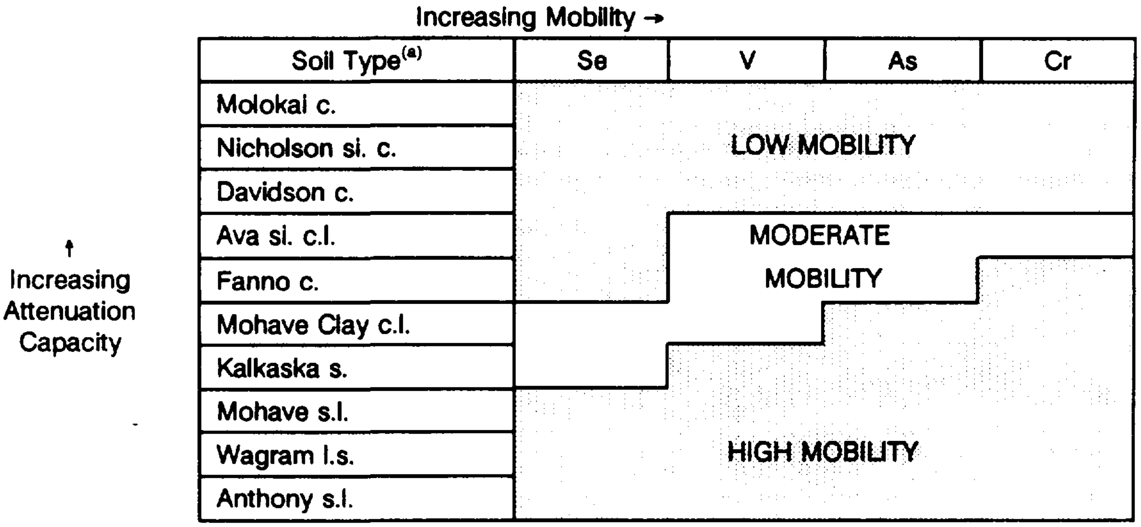


(a) See Table 3-2 for soil characteristics.
c = clay; si = silt; l = loam; and s = sand.

(b) Ranking of metal mobility based on anaerobic landfill conditions.

Adapted from Korte et al. (1976) with permission of the authors and of the publisher, Williams & Wilkins.

Figure 3-1. Relative mobility of cations through soil.(a)(b)



(a) See Table 3-2 for soil characteristics.
c = clay; si = silt; l = loam; and s = sand.

(b) Ranking of metal mobility based on anaerobic landfill conditions.

Adapted from: Korte et al. (1976) with permission of the authors and of the publisher, Williams & Wilkins.

Figure 3-2. Relative mobility of anions through soil.(a)(b)

3.2.1 Arsenic

3.2.1.1 Transport and Partitioning of Arsenic

Most arsenic at contaminated sites exists in soils. Because many arsenic compounds are strongly sorbed onto soils or sediments, leaching by rainfall or snowmelt usually results in transport of these compounds over only short distances in soils (Moore et al., 1988; Welch et al., 1988). Transport and partitioning of arsenic in water depend on chemical forms (e.g., oxidation state and associated opposite charge ion) and interactions with other materials present. Soluble forms move with water and may be carried long distances via rivers. However, arsenic may be adsorbed onto sediments or soils, especially clays, iron oxides, aluminum hydroxides, manganese compounds, and organic materials (Welch et al., 1988).

Sediment-bound arsenic may be released back into the water by chemical or biological interconversions. Bioconcentration of arsenic can occur in aquatic organisms, primarily in algae and the lower invertebrates. However, biomagnification in aquatic food chains does not appear to be significant (Callahan et al., 1979), although some fish and invertebrates contain high levels of arsenic compounds. Terrestrial plants may accumulate arsenic by root uptake from the soil or by absorption of airborne arsenic deposited on the leaves, and certain species may accumulate substantial levels. Arsenic in the atmosphere exists as particulate matter, mostly as particles of less than 2 μm in diameter (Coles et al., 1979). Examples of industrial processes that generate airborne arsenic particulates include smelting and glass making. These particles are transported by wind until they are returned to earth along with precipitation or by dry deposition.

3.2.1.2 Transformations of Arsenic in the Environment

Air--

Arsenic is released into the atmosphere primarily as arsenic trioxide or arsine and its methyl derivatives. Arsine is rapidly oxidized in the atmosphere; trivalent arsenic and methyl arsines may be more persistent because of their lower rates of oxidation. Trivalent arsenic and methyl arsines are oxidized partially to the pentavalent state and coexist with pentavalent forms as a mixture (Callahan et al., 1979).

Soils and Sediments--

Most arsenic compounds are strongly sorbed by soils and sediments and thus are relatively immobile. As(V) compounds predominate in aerobic soils and sediments; As(III) compounds in slightly reduced soils and sediments; and arsine, methylated arsines, and arsenic metal in very reduced conditions. Arsine and methylated derivatives are highly volatile and will vaporize after formation. As(V) and As(III) compounds are sorbed through specific adsorption onto iron and aluminum hydrous oxides, clays, and carbonates. They also can be removed from water through coprecipitation with iron oxides or by isomorphic substitution with phosphorus in minerals. Coprecipitation and adsorption with hydrous iron oxides may be the most common mechanisms under most environmental conditions.

In general, arsenates are more strongly sorbed by soils and sediments than are arsenites. Arsenates also are fixed to soils and sediments by adsorption, forming immobile species with soil minerals containing iron, aluminum, calcium, manganese, and other similar minerals. In fact, arsenates may be leached from soils if the levels of reactive iron, aluminum, and calcium in soils are low (Woolson et al., 1971). The presence of iron in soils and sediments can be most effective in controlling arsenate mobility (Krause and Ettel, 1989; Masscheleyn et al., 1991).

Arsenic compounds in soils and sediments can undergo a complex series of transformations, including oxidation-reduction reactions, ligand exchange, and biotransformation (Callahan et al., 1979; Welch et al., 1988). The factors most strongly influencing these fate processes include oxidation-reduction conditions (Eh), pH, the presence of certain competing anions and complexing ions, clay and hydrous oxide contents, metal sulfide and sulfide ion concentrations, salinity, and distribution and composition of the biota (Callahan et al., 1979; Wakao et al., 1988; Bodek et al., 1988). Sorbed As(V) compounds in sediments may be remobilized if conditions become sufficiently reduced for As(III) compounds to form. Arsenic also appears to be more mobile under both alkaline and more saline conditions. The presence of other ions and organic compounds can increase arsenic mobility because of competitive sorption and the formation of organoarsenic complexes. Arsenic may be biotransformed through methylation to form highly volatile arsine and its methyl derivatives, thus being transferred from sediments back to the water column in aquatic systems.

Surface Water and Groundwater--

Transformations of arsenic in surface water and groundwater are similar to those occurring in soils and sediments. The predominant form of arsenic in surface water usually is arsenate, but aquatic microorganisms may reduce the arsenate to arsenite and a variety of methylated arsenicals. Arsenate also occurs in groundwater but typically sorbs onto iron-bearing minerals so arsenite is often the major component in the water, depending on the characteristics of the water and the surrounding geology (Welch et al., 1988).

3.2.2 Cadmium

3.2.2.1 Transport and Partitioning of Cadmium

Cadmium and cadmium compounds may exist in air as suspended particulates derived from industrial emissions, combustion of fossil fuels, smelting operations, or soil erosion. Depending on particle size, the particulate matter may be transported from a hundred to a few thousand kilometers (with a typical atmospheric residence time of 1 to 10 days) before deposition along with precipitation, or may be removed from the atmosphere by gravitational settling in the areas downwind from the pollutant source. The particulates also may dissolve in atmospheric water droplets and be removed by wet deposition. Cadmium is more mobile in aquatic environments than most other heavy metals, such as lead (Callahan et al., 1979). Cadmium exists in water as hydrated ions or Cd complexes with humic substances or other organic ligands. Cadmium may be removed from water by precipitation or by sorption to mineral surfaces and organic materials. Studies have revealed that cadmium concentrations in sediments are at least one order of magnitude higher than in the overlying water (Callahan et al., 1979). However, cadmium may redissolve from sediments under varying ambient conditions. Cadmium in soils may leach into water, especially under acidic conditions. Cadmium does not form volatile compounds; therefore, partitioning from water to the air does not occur. Aquatic and terrestrial organisms bioaccumulate cadmium. Cadmium concentrations in freshwater and marine animals can be hundreds to thousands of times higher than in water (Callahan et al., 1979). Cadmium is known to accumulate in grasses, food crops, poultry, cattle, and wildlife. However, biomagnification of cadmium through the food chain is not clearly understood (Beyer, 1986).

3.2.2.2 Transformations of Cadmium in the Environment

Air--

Most cadmium compounds found in air are stable and are not subject to chemical reactions. Transformation of these compounds is mainly through dissolution in water or in dilute acids.

Soils and Sediments--

Precipitation and adsorption onto soils and sediments are the most common mechanisms governing the transformation and mobility of cadmium in the environment. Removal of cadmium from water increases with increasing pH through a critical range of 6 to 8. Below pH 6, little or no cadmium is removed. Above pH 8 to 9, cadmium may be completely removed. Cadmium adsorption often correlates with the cation exchange capacity (CEC) of the clay minerals, carbonate minerals, oxides, and organic matter in soils and sediments. The presence of anions and ligands also affects cadmium adsorption. For example, sulfate and chloride ions often reduce cadmium adsorption by amorphous clay minerals, silica, and/or alumina. On the contrary, ligands such as humic acids, glycine, and phosphate increase cadmium adsorption. The presence of other cations also reduces cadmium adsorption because of competitive adsorption.

Surface Water and Groundwater--

In surface water and groundwater, cadmium is present primarily as Cd^{2+} ions, although at high concentrations of organic matter, a significant amount of Cd^{2+} ions may complex with the organic matter. In the acidic environments and in the presence of chloride and sulfate, cadmium may form complexes with chloride or sulfate ions. The formation of these complexes may keep cadmium in the aqueous phase, thus increasing its mobility. In reducing environments, cadmium precipitates with sulfide to form CdS. Precipitation of CdS provides an effective control on cadmium mobility as long as reducing conditions are maintained.

3.2.3 Chromium

3.2.3.1 Transport and Partitioning of Chromium

Chromium is present in the atmosphere primarily as particulate matter. Transport and partitioning of this particulate matter depend largely on particle size and density. Chromium particles of <20 µm may remain airborne for longer periods of time and be transported for greater distances than larger particles. These particles are deposited on land or water via dry or wet deposition. Cr(VI) at metal-contaminated sites can be reduced to Cr(III) by soil organic matter and Fe(II) minerals. The rate of this reduction reaction is slow, but it increases with decreasing soil pH. Cr(III) is readily adsorbed by soil or forms insoluble $Cr(OH)_3$ or $Cr_2O_3 \cdot nH_2O$, depending on soil pH. Therefore, Cr(III) is relatively immobile in soils in contrast to Cr(VI). Formation of complexes with soluble organic matter, however, increases the mobility of Cr(III) in soils.

The mobility of chromium in soil also depends on the sorption characteristics of the soil; the determining factors are clay content, Fe_2O_3 content, and organic matter content. Surface runoff from soil can transport both soluble and bulk precipitates of chromium to surface water. Soluble and unadsorbed Cr(VI) and Cr(III) complexes in soil will leach into groundwater. The leachability of Cr(VI) in the soil increases as the soil pH increases. On the other hand, the lower pH of acid rain may enhance the leaching of acid-soluble Cr(III) and Cr(VI) compounds in soil. Most of the chromium released into water ultimately will be deposited in sediment. The remaining soluble chromium is present as Cr(VI) and soluble Cr(III) complexes. As in soils, Cr(VI) in water eventually will be reduced to Cr(III) by organic matter in the water. It has been estimated that the residence time of total chromium in lake water ranges from 4.6 to 18 years (Fishbein, 1984; Schmidt and Andren, 1984). While bioaccumulation of chromium occurs to a limited extent, biomagnification of chromium is not expected in either the aquatic or terrestrial food chain.

3.2.3.2 Transformations of Chromium in the Environment

Air--

Cr(VI) in the atmosphere may be reduced by vanadium (V^{2+}, V^{3+}, and VO^{2+}), Fe^{2+}, HSO_3-, and As^{3+}. No other reactions are likely under most environmental conditions.

Soils and sediments--

The fate of chromium in soil is dependent partly on soil pH and redox potential. Cr(VI) exists in more oxidized soils and sediments. Cr(III) may be oxidized to Cr(VI) in the presence of excess MnO_2 (Fendorf and Zasoski, 1992). Cr(III)-organic complexes (such as humic acid) may be more easily oxidized than insoluble $Cr(OH)_3$ and Cr_2O_3. In deeper soils and sediments where anaerobic conditions exist, Cr(VI) is reduced to Cr(III) in the presence of reducing agents (e.g., organic matter, S^{2-}, Fe^{2+}, etc.). The reduction of Cr(VI) to Cr(III) also is possible in aerobic soils and sediments containing organic energy sources necessary for the redox reaction. This reduction reaction proceeds more favorably at acidic pH values. In most soils and sediments, most chromium eventually will be present as Cr(III).

Surface Water and Groundwater--

One of the most widely known cases of Cr(VI) groundwater contamination is the Nassau County Superfund site on Long Island, New York (Palmer and Wittbrodt, 1991), where a recharge basin used for the disposal of 40 mg/L Cr(VI) solutions from an aircraft plant became a source of a thin and elongated plume migrating 1,300 m downgradient from the basin at the same velocity as the groundwater. The Cr(VI) plume was then discharged into Massapequa Creek. Very high levels of groundwater contamination by Cr(VI) also have taken place at the United Chrome Products site in Corvallis, Oregon, which was a hard chrome plating facility operating from 1956 until 1985. After operations ceased, it was discovered that the process tanks had been leaking directly to the groundwater and that a plume of 14,600 mg/L Cr(VI) migrated approximately 100 m downgradient and the contaminated water had discharged into the local drainage system. The contaminated soils contained as much as 25,900 mg/kg of Cr(VI).

After being released into surface water and groundwater, Cr(VI) will precipitate with metal cations, such as Ba^{2+}, Pb^{2+}, and Ag^{+}. Under anaerobic conditions, Cr(VI) will be reduced to Cr(III) by S^{2-} or Fe^{2+} ions with a reduction half-life ranging from instantaneous to a few days (Saleh et al., 1989). However, the reduction of Cr(VI) by organic energy sources is much slower, depending on the type and amount of organic material and the redox condition of the water. The transformation of chromium in groundwater depends on the redox and pH conditions in the aquifer. Cr(VI) usually predominates in shallow aquifers where aerobic conditions exist. Cr(III) predominates in deeper groundwater under reducing conditions because of Eh. Because the pH in most groundwater ranges from 6 to 8, CrO_4^{2-} predominates.

Cr(III), after being released into surface water and groundwater, forms complexes with dissolved organic matter, adsorbs onto suspended clay and oxide particles, or precipitates as $Cr(OH)_3$ or Cr_2O_3 solids at pH >5. The oxidation of Cr(III) to Cr(VI) is insignificant, even in well-aerated water. The presence of MnO_2 will accelerate this reaction, but only decreasing the oxidation half-life from 9 years to 2 years (Saleh et al., 1989). The predominant Cr(III) species in this pH range is $Cr(OH)_2^{1+}$. This and other Cr(III) species will predominate at more acidic pH values; $Cr(OH)_3$ and $Cr(OH)_4^{1-}$ predominate in more alkaline pH values (Calder, 1988).

3.2.4 Lead

3.2.4.1 Transport and Partitioning of Lead

Lead exists in the atmosphere primarily in the particulate form. Upon release to the atmosphere, lead particles are dispersed and ultimately are removed from the atmosphere by wet or dry deposition. In general, wet deposition is more predominant than dry deposition. Particles with diameters of >2μm settle out of the atmosphere fairly rapidly and are deposited relatively close to emission sources, whereas smaller particles may be transported thousands of kilometers. For example, lead has been found in sediment cores of lakes in Ontario and Quebec, provinces in Canada that were far removed from any point sources of lead releases (Evans and Rigler, 1985). Lead is removed from the atmosphere by wet deposition relatively quickly, compared to metals such as Fe, Al, Mn, Cu, Zn, and Cd.

The fate of lead in soil is affected primarily by processes such as adsorption, ion exchange, precipitation, and complexation. After being released to a contaminated site, most lead is retained strongly in soil (by ion exchange, precipitation, or sorption/complexation to organic matter); very little is transported into surface water or groundwater. In soil with a high organic matter content and a pH of 6 to 8, lead may form insoluble organic lead complexes; if the soil has less organic matter at the same pH, hydrous lead oxide complexes or lead carbonate or lead phosphate precipitates may form. At a pH of 4 to 6, the organic lead complexes become more soluble and may leach out. Lead also may be converted, at the soil surface, to lead sulfate, which is relatively more soluble than lead carbonates or lead phosphates.

The amount of lead in water depends on water pH and the total dissolved salt content. At pH >5.4, the lead solubility is approximately 500 μg/L in soft water and only 30 μg/L in hard water. Sulfate ions limit the lead concentration in solution by forming lead sulfate. Above pH 5.4 or 6, lead carbonates, $PbCO_3$ and $Pb_2(OH)_2CO_3$, form. As a result, a significant fraction of lead carried by river water is in an undissolved form, which consists of colloidal or larger particles of lead carbonate, lead oxide, lead hydroxide, or lead sulfate. Lead also may occur as sorbed ions or surface coatings on sediment mineral particles or it may be carried as a part of suspended living or nonliving organic matter in water.

Plants and animals may bioconcentrate lead, but biomagnification has not been detected. In general, the highest lead concentrations are found in aquatic and terrestrial organisms that live near lead mining, smelting, and refining facilities; storage battery recycling plants; or sewage sludge and spoil disposal areas; and in lead-contaminated sites.

3.2.4.2 Transformations of Lead in the Environment

Air--

Lead particles emitted from mines and smelters are primarily in the form of PbO, $PbSO_4$, and PbS. In the atmosphere, lead exists primarily in the form of $PbSO_4$ and $PbCO_3$. It is not completely clear how the chemical composition of lead changes during dispersion in the atmosphere. Several studies have suggested that tetraalkyl and trialkyl lead are the important intermediates during lead transformation in the atmosphere (U.S. Department of Health and Human Services, 1991d). The transformation involves direct photolysis, reaction with hydroxyl radicals, and reaction with ozone.

Soils and Sediments--

Atmospheric lead enters the soil as lead sulfate or it is converted rapidly to lead sulfate at the soil surface. Lead in the contaminated sites is strongly retained in soil and sediment in the form of divalent lead cation, lead carbonates, lead sulfate, and lead sulfide. Lead also forms complexes with soil organic matter. Tetramethyl lead, a relatively volatile organolead compound, may form as a result of biological alkylation of organic and inorganic lead by microorganisms in anaerobic sediments. If the water over the sediments is aerobic, volatilization of tetramethyl lead from the sediments is not considered to be important because the tetramethyl lead will be oxidized (U.S. EPA, 1979, EPA-440/4-79-029a).

Surface Water and Groundwater--

In surface water and groundwater, the divalent lead (Pb^{2+}) is the stable ionic species of lead. It precipitates with hydroxide, carbonate, sulfide, and sulfate depending on the water pH and the dissolved salt content of the water. At pH <5.4, lead sulfate limits the concentration of lead in solution, whereas at pH >5.4, lead carbonates limit the lead concentration. Tetraalkyl lead compounds formed in the anaerobic sediment are subject to photolysis and volatilization after being released from the sediment to the surface water. Degradation proceeds from trialkyl lead to dialkyl lead to inorganic lead. Because triethyl and trimethyl lead are more water-soluble, they are more persistent in water than tetraethyl or tetramethyl lead.

3.2.5 Mercury

3.2.5.1 Transport and Partitioning of Mercury

The transport and partitioning of mercury are characterized by degassing of the metal from soils and surface waters, followed by atmospheric transport, deposition of mercury back to land and surface waters, and sorption of the compound to soil or sediment particulates. The redox potential and pH of the environmental medium determine the specific state and form of mercury. Metallic mercury, the most reduced form, is a liquid at ambient temperatures but readily vaporizes. It is the principal form of mercury in the atmosphere, which can be transported long distances before wet and dry deposition processes return the compound to land and surface waters. Residence time in the atmosphere ranges from 6 to 90 days (Andren and Nriagu, 1979) to 0.3 to 2.0 years (U.S. EPA, 1984, EPA/600/8-84/019F).

In soils and surface waters, volatile forms (e.g., metallic mercury and dimethylmercury) evaporate to the atmosphere, whereas solid forms partition to particulates. Mercury exists primarily in the mercuric and mercurous forms as a number of complexes with varying water solubilities. In soils and sediments, sorption is one of the most important controlling pathways for removal of mercury from solution; sorption usually increases with increasing pH. Other removal mechanisms include flocculation, co-precipitation with sulfides, and organic complexation. Mercury is strongly sorbed to humic materials. For example, in the St. Lawrence River, the total dissolved mercury concentration was 12 mg/L, of which 70% was associated with organic matter. Inorganic mercury sorbed to soils is not readily desorbed; therefore, freshwater and marine sediments are important repositories for inorganic mercury. In general, leaching is a relatively insignificant transport process in soils, but surface runoff does remove mercury from soil to water, particularly for soils with high humic content.

The most common organic form of mercury, methylmercury, is soluble and mobile, and it quickly enters the aquatic food chain; concentrations of methylmercury in carnivorous fish can be 10,000 to 100,000 times the concentrations found in ambient waters (Callahan et al., 1979). Biomagnification has been found also in piscivorous fish. Aquatic macrophytes also bioconcentrate methylmercury. Bioaccumulation of methylmercury in the aquatic food chain is important because it generally is the most important source of nonoccupational human exposure to the compound. Aquatic plants also bioaccumulate mercury.

3.2.5.2 Transformations of Mercury in the Environment

Mercury is transformed in the environment by biotic and abiotic oxidation and reduction, bioconversion of organic and inorganic forms, and photolysis of organic mercurials. Inorganic mercury can be methylated by microorganisms indigenous to soils, fresh water, and salt water. This process is mediated by various microbial populations under both aerobic and anaerobic conditions.

Air--

The main transformation process for mercury compounds in the atmosphere is photolysis of organomercurials. Metallic mercury vapor also may be oxidized to other forms in the removal of the compounds from the atmosphere by precipitation. The oxidation of mercury with dissolved ozone, hydrogen peroxide, hypochlorite entities, or organoperoxy compounds or radicals also may occur in the atmosphere. Some mercury compounds, such as mercuric sulfide, are quite stable in the atmosphere as a result of their binding to particles in the aerosol phase.

Soils and Sediments--

Mercury (II) usually forms various complexes with chloride and hydroxide ions in soils; the specific complexes formed depend on the pH, salt content, and composition of the soil solution. Formation and degradation of organic mercurials in soils are mediated by the same types of microbial processes occurring in surface waters, and also may occur through abiotic processes. Elevated levels of chloride ions reduce methylation of mercury in river sediments, sludge, and soil, although increased levels of organic carbon and sulfate ions increase methylation in sediments. Mercurous and mercuric mercury also are immobilized in soils and sediments by forming precipitates with carbonate, phosphate, sulfate, and sulfide.

Surface Water and Groundwater--

The most important transformation process in the environmental fate of mercury in surface water and groundwater is biotransformation. Any form of mercury entering surface water and groundwater can be microbially converted to methylmercuric ion given favorable conditions. Sulfur-reducing bacteria are responsible for most of the mercury methylation in the environment, with anaerobic conditions favoring their activity. Volatile elemental mercury may be formed through the demethylation of methylmercury or the reduction of inorganic mercury, with anaerobic conditions favoring the reactions. High pH values and increased dissolved organic carbon levels in water reduce methylation of mercury in water. At pH 4 to 9 and a normal sulfide concentration, mercury forms mercury sulfide, which precipitates out and removes mercury ions from the water. Under more acidic conditions, however, the activity of the sulfide ion decreases, thus inhibiting the formation of mercury sulfide and favoring the formation of methylmercury. Abiotic reduction of mercuric mercury to metallic mercury in aqueous systems also can occur, particularly in the presence of soluble humic substances. This reduction process is enhanced by light, occurs under both aerobic and anaerobic conditions, and is inhibited by the competition from chloride ions.

3.3 TOXICITY

The following is an outline of toxicity information about arsenic, cadmium, chromium, mercury, and lead. Target organs, exposure pathways, and environmental fate and ecological effects are summarized in Table 3-3. More detailed information on environmental fate and transport and toxicity for metals is available in metal-specific toxicology profiles (U.S. Department of Health and Human Services, 1991a, 1991b, 1991c, 1991d, and 1992). Recent updates on toxicology are available through the Integrated Risk Information System (IRIS) (see Appendix H, Subsection H.3.5). Information in this subsection is derived from these sources. Information on Center for Exposure Assessment Modeling (CEAM)-supported models is available on line (see Appendix H, Subsection H.3.6). Information on available groundwater modeling programs is provided in IGWMC (1993), NRC (1990), and U.S. EPA (1988, EPA/600/2-89/028). Information on available air models is provided in U.S. EPA (1986, EPA/450/2-78-027R).

TABLE 3-3. RISK ASSESSMENT CONCERNS: METALS

Contaminants	Target Organs/Effects	Exposure Pathways	Environmental Fate/Ecological Effects
Arsenic[(a)]	Human carcinogen (Group A) by inhalation (lung cancer) and ingestion (skin cancer); may also be associated with increased incidence of cancer of the colon, liver, and spleen; may cause damage to nerves and adverse reproductive effects	Inhalation of dust, fumes; ingestion of contaminated food, soil, groundwater, surface water	Metals do not biodegrade and therefore are highly persistent in the environment; aquatic toxicity decreases with increased pH and hardness of water; disturbs soil microbial activity; affects plant metabolism; volatilization in aquatic environments caused by biological activity and reducing conditions
Cadmium[(a)]	Affects cardiovascular and immune systems, kidneys, liver; human carcinogen by inhalation causing lung tumors and possibly prostate cancer (B_1); animal teratogen	Inhalation of dust, fumes, ingestion of contaminated food, soil, groundwater, surface water	Metals do not biodegrade and therefore are highly persistent in the environment; aquatic toxicity decreases with increased pH and hardness of water; disturbs soil microbial activity; affects plant metabolism; volatilization in aquatic environments caused by biological activity and reducing conditions
Chromium[(a)]	Hexavalent form affects gastrointestinal (GI) tract, kidney, respiratory system, and is a human carcinogen (A); the primary effect of the trivalent form is dermatitis	Inhalation of dust; ingestion of contaminated food, groundwater, surface water, soil	Bioaccumulates in aquatic organisms; trivalent form is more acutely toxic to fish, whereas hexavalent form is more chronically toxic
Lead	Neurotoxic to children even at low-level exposure; causes alterations in blood-forming system and Vitamin D regulation; Centers for Disease Control determined child blood levels about 25 μg/dl indicate excessive lead absorption; probable carcinogen (B_1)	Inhalation of dust, fumes; ingestion of contaminated food, soil, groundwater, surface water; absorption rate highest through inhalation	Persistent; bioaccumulates; substantial background levels already present in the environment[(b)]
Mercury	Organic compounds more acutely toxic than inorganic; affects central nervous system (CNS), respiratory system, liver, kidney, and GI tract; teratogenic and embryotoxic in animals; skin/eye irritant	Inhalation of dust, fumes; ingestion of contaminated food, soil, groundwater, surface water	Highly bioaccumulative and toxic to aquatic biota; persistent; atmospheric transport is the primary migration pathway

Source: Adapted from U.S. EPA, Annotated Technical Reference.

(a) Cancer potency factor currently available (see Table 3-4).

(b) Because lead is a ubiquitous compound in the environment, background exposure must be considered in addition to the exposure levels identified for the site. Background exposure to lead is the result of atmospheric dust; lead solder from cans; metals used in grinding, crushing, and sieving; and lead in water. In urban areas, lead is often found in lead-based paint or at elevated background levels in soil due to lead in auto emissions. The decision to clean up beyond the background level should be considered on a site-specific basis..

TABLE 3-4. CONSTANTS FOR ANALYSIS OF ENVIRONMENTAL RISK FROM METAL CONTAMINANTS

	Reference Doses and Cancer Potency Slopes			
Contaminant	Oral RfD (mg/kg/d)	Inhaled RfD (mg/kg/d)	Oral Potency Slope 1/(mg/kg/d)	Inhaled Potency Slope 1/(mg/kg/d)
Arsenic	3.00e-04	ND	ND	ND
Arsenic (as carcinogen)	ND	ND	1.75e+00	1.51e+01
Cadmium & compounds	5.00e-04	ND	ND	6.30e+00
Chromium(III) & compounds	1.00e+00	5.71e-07	ND	ND
Chromium(VI) & compounds	5.00e-03	ND	ND	4.20e+01
Lead (inorganic)	ND	ND	ND	ND
Lead (tetraethyl)	1.00e-07	ND	ND	ND
Mercury & compounds (inorganic)	3.00e-04	8.57e-05	ND	ND
Mercury & compounds (methyl)	3.00e-04	ND	ND	ND

Source: Smith, 1993. Check IRIS database (see Appendix H) for updates.
RfD = reference dose; ND = No data.

Potential risk from carcinogenic effects is expressed as a probability (i.e., 1E-06) which translates, in this example, to an additional cancer in an exposed population of 1 million. Risk estimates represent the incremental probability that an individual will develop cancer over a lifetime as a result of exposure to the contaminant. The probabilities are determined by multiplying the estimated chronic daily intake (CDI), as determined by the exposure scenario, by the compound-specific cancer potency slope (CPS) (see Table 3-4).

Potential risk from noncarcinogenic effects is characterized by the hazard quotient (HQ). The hazard quotient is the ratio of the CDI divided by a compound-specific reference dose (RfD) (see Table 3-4). The RfD is defined as an estimate of the daily exposure level for the human population, including sensitive subpopulations, that is likely to be without an appreciable risk of deleterious effects during a lifetime. In the case of multiple contaminants, the HQs for each contaminant are summed to give a hazard index (HI). Generally HI values greater than one indicate cause for concern.

3.3.1 Arsenic

Arsenic is a common environmental toxicant due both to natural releases such as mineral springs and to mining, smelting, and the use of arsenic compounds. Arsenic exists as the elemental form and in trivalent and pentavalent oxidation states. The toxicity of arsenic typically increases in the order RAs-X < As(V) < As(III) < arsine (AsH_3). The level of toxicity is generally related to the rate of clearance from the body with the organic arsenical being eliminated most quickly.

EPA has set a limit of 50 ppb for arsenic in drinking water. EPA is currently reviewing this value and may lower it. Finally, the Occupational Safety and Health Administration (OSHA) has established a maximum permissible exposure limit of 10 $\mu g/m^3$ for airborne arsenic in various workplaces that use inorganic arsenic.

3.3.2 Cadmium

Cadmium ranks close to lead and mercury as a metal of current toxicological concern. Cadmium is released from industrial use. It is also present in coal and other fossil fuels and is emitted as a result of fuel combustion. Cadmium is poorly absorbed in the gastrointestinal (GI) tract but is more readily absorbed on inhalation, particularly for smokers.

The EPA now allows 10 parts per billion (ppb) of cadmium in drinking water, and plans to reduce the limit to 5 ppb. The EPA limits how much cadmium can be put into lakes, rivers, dumps, and cropland. The EPA does not allow cadmium in pesticides. The Food and Drug Administration (FDA) limits the amount of cadmium in food colors to 15 ppm.

OSHA now limits work place air to 100 μg cadmium/m^3 as cadmium fumes and 200 μg cadmium/m^3 as cadmium dust. OSHA is planning to limit all cadmium compounds to either 1 or 5 μg/m^3. Because breathing cadmium may cause lung cancer, the National Institute for Occupational Safety and Health (NIOSH) wants workers to breathe as little cadmium as possible.

3.3.3 Chromium

Chromium enters the atmosphere as a result of fossil fuel burning, steel production, stainless steel welding, and chromium manufacturing. Emissions to water and soil can result from industrial processes such as electroplating, tanning, water treatment, or disposal of coal ash. Cr(III) is an essential micronutrient that helps the body use sugar, protein, and fat. Higher exposures to Cr(III) can produce toxic effects. The oxidized form, Cr(VI), is more toxic than Cr(III).

EPA has set the maximum level of Cr(III) and Cr(VI) allowed in drinking water at 0.05 mg Cr per liter of water (mg/L). According to the EPA, the following levels of Cr(III) and Cr(VI) in drinking water are not expected to cause harmful effects: 1.4 mg Cr/L water for 10 days of exposure for children, 0.24 mg Cr/L water for longer-term exposure for children, 0.84 mg Cr/L for longer-term exposure for adults, and 0.12 mg Cr/L water for lifetime exposure of adults.

OSHA regulates chromium levels in the work place air. The occupational exposure limits for an 8-hour workday, 40-hour workweek are 0.5 mg Cr/m^3 for water-soluble chromic (Cr[III]) or chromous (Cr[II]) salts and 1 mg Cr/m^3 for metallic chromium (Cr[0], and insoluble salts). The level of chromic acid and Cr(VI) compounds in the workplace air should not be higher than 0.1 mg Cr(VI)/m^3 for any period of time.

For Cr(VI) compounds that do not cause cancer, NIOSH recommends an exposure limit of 0.025 mg Cr(VI)/m^3 for a 10-hour workday, 40-hour workweek. The levels of the Cr(VI) compounds that do not cause cancer should not be greater than 0.05 mg Cr(VI)/m^3 for any 15-minute period. For Cr(VI) compounds that do cause cancer, NIOSH recommends an exposure limit of 0.001 mg Cr(VI)/m^3 for a 10-hour workday, 40-hour workweek.

3.3.4 Lead

Lead enters the air, water, and soil through a variety of human activities. Until recently a major source was tetraethyl-lead in gasoline. Both the gastrointestinal tract and the respiratory system are major routes for lead absorption.

EPA requires that the concentration of lead in air that the public breathes shall not exceed 1.5 μg/m^3 averaged over 3 months. EPA now regulates the limit of level of lead in leaded gasoline to 0.1 gram per gallon (0.1 g/gal) and the level in unleaded gasoline to 0.001 g/gal.

EPA regulations also limit lead in drinking water to 0.015 milligrams per liter (mg/L). OSHA regulations limit the concentration of lead in workroom air to 50 $\mu g/m^3$ for an 8-hour workday.

As shown in Table 3-4, there currently are no criteria (i.e., cancer slope factor or reference dose) available for lead. In September 1989, the U.S. EPA recommended a soil lead cleanup level of 500 to 1,000 mg/kg for residential sites with a direct exposure route (U.S. EPA, 1989, OSWER Directive 9355.4-02) and, in January 1990, reiterated that these interim soil cleanup levels were guidance, not binding regulation (U.S. EPA, 1990, OSWER Directive 9355.4-02A). There is a general trend away from using single-value criteria for lead cleanup standards and instead using a model that accounts for population, health, and environmental factors. The U.S. EPA is developing guidance recommending the use of the Uptake Biokinetic (UBK) model which integrates exposure from lead in air, water, soil, diet, dust, and paint with pharmacokinetic modeling to predict blood levels of lead in the most sensitive population (children 0 to 6 years old). The model does not apply to adults and it may not be appropriate if the exposure scenario is an industrial setting. Therefore, recommended soil cleanup levels for lead at commercial or industrial sites are not available at this time. The method for calculating a target soil/dust lead guideline concentration proposed by the Society for Environmental Geochemistry and Health is outlined by Wixson and Davies (1994). A copy of the 1991 Strategy for Reducing Lead Exposures can be obtained by calling the TSCA Assistance Information Service at (202) 554-1404 or faxing a request to (202) 554-5603.

3.3.5 Mercury

Mercury enters the environment through industrial use and as a component of fossil fuels. When considering the toxicity of mercury, three chemical forms must be recognized: (1) elemental mercury, (2) salts of mercury, (3) and organic mercurials. Elemental mercury is the most volatile inorganic form. Most exposures to elemental mercury vapor are occupational. The monovalent and divalent mercuric salts are the most irritating and acutely toxic forms of the metal. There is a wide range of organic forms of mercury. The alkylmercury forms are the most toxic with methylmercury being the most commonly occurring example.

EPA and the FDA have set a limit of 2 parts mercury per billion (ppb) parts of water in drinking water. EPA also recommends that the level of inorganic mercury in rivers, lakes, and streams should be no more than 144 parts mercury per trillion (ppt) parts of water to protect human health. EPA suggests that a daily exposure to 2 ppb of mercury in drinking water for an adult of average weight is not likely to cause any significant adverse health effects.

OSHA regulates levels in the workplace. It has set a limit of 10 $\mu g/m^3$ for organic mercury and 50 $\mu g/m^3$ for inorganic mercury in the workplace air to protect workers during an 8-hour shift and a 40-hour workweek.

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SECTION 4

REMEDIAL OPTIONS

This section details the specific considerations and issues related to the performance and application of technologies or particular treatment trains for remediation of metal-contaminated sites. Final decisions for selecting a treatment strategy will depend on technology- and site-specific issues related to implementation, performance, costs, and the ability to achieve site remediation goals. Evaluation of each treatment approach will require consideration of the contaminated medium, the nature and type of contamination, and the remediation goals established for the site. The basic options for site treatment selection relative to remediation objectives are discussed in Subsections 4.1 through 4.5. A summary evaluation of the technologies with respect to the Remedial Investigation/Feasibility Study (RI/FS) evaluation criteria is shown in Appendix G (Table G-1).

Remediation strategies for metal-contaminated sites may incorporate several distinct technology options assembled into a treatment train to attain specific site cleanup goals. Discussion of metal-contaminated site remediation technologies presented in this section evaluates the performance and adequacy of each technology in achieving the desired toxicity reduction, reduction of the environmental mobility of metal contamination, and significant volume reduction of the contaminant. Depending on the goals and criteria for site remediation, the following control options and basic approaches to toxicity/mobility/volume reductions are available:

- Immobilization Treatment: Discussion of these processes is presented in Subsection 4.2.
- Separation/Concentration Treatment: Discussion of these processes relative to soils, sediments, and sludges is presented in Subsection 4.3. Both ex situ (Subsection 4.3.1) and in situ (Subsection 4.3.2) technologies are addressed. Literature sources describing separation/concentration technologies for contaminated groundwater are outlined in Subsection 4.4.

In some cases, specific trade names or vendors are mentioned to assist site personnel in identifying sources of additional information on technologies. Mention of specific sources should not be construed as an endorsement of the source or technology.

4.1 CLEANUP GOALS

4.1.1 Major Regulatory Sources for Applicable or Relevant and Appropriate Requirements

General information on the identification and determination of potential applicable or relevant and appropriate requirements (ARARs) for remedial actions at Superfund metal-contaminated sites are presented in Appendix J. The information presented in this section is not meant to be an exhaustive discussion on the compliance with ARARs, but rather a representative listing of potential ARARs and areas of consideration.

The following principal statutes should be examined as potential ARARs at metal sites:

- Safe Drinking Water Act
- Clean Water Act
- Water Quality Criteria

- Comprehensive Environmental Response, Compensation, and Liability Act
- Resource Conservation and Recovery Act
- Clean Air Act
- Occupational Safety and Health Act
- Department of Transportation Rules

4.1.2 Soil and Groundwater Cleanup Goals for Arsenic, Cadmium, Chromium, Lead, and Mercury at Selected Superfund Sites

Cleanup goals are one of the most important of the regulatory requirements that will determine whether a treatment option is potentially acceptable. Table 4-1 summarizes the cleanup goals determined for a variety of metal-contaminated sites. Cleanup goals are developed based on a site-specific risk assessment. Cleanup goals may be stated either as total metal content or leachable metal content depending on the risk assessment and the technology selected. Treatability standards must be expressed in terms consistent with the type of treatment option. For technologies designed to reduce contaminant mobility (for example solidification/stabilization or vitrification), performance goals for the treated waste are stated as leachable metal content. Toxicity Characteristic Leaching Procedure (TCLP) (see Table 4-2) or other leaching data generally will be required to demonstrate that the treatment option immobilizes the contaminants. Particularly when the treated waste is discarded on-site, the immobilization technologies (containment, solidification/stabilization, and vitrification) addressed in this document pose a degree of risk to human health and the environment not shared by processes that remove the toxic metals from the waste. The performance standards and monitoring requirements applied to immobilized wastes should be selected to ensure low leaching potential in the disposal environment, physical durability, and chemical stability of the treated waste system. For an in-depth discussion on performance measures, see *Technical Resource Document: Solidification/Stabilization and its Application to Waste Materials* (EPA/530/R-93/012), June 1993. The performance standards for technologies to remove metals (for example metal extraction) generally will be stated as total metal concentration remaining in the treated residual.

4.2 IMMOBILIZATION TREATMENT

This subsection discusses technologies that reduce the mobility of contaminants in a solid matrix or the transport of contaminated groundwater by one or more of the following three mechanisms:

1. Reducing infiltration of fluids into the contaminated media by using barriers.
2. Reducing infiltration of fluids by modifying the permeability of the contaminated matrix.
3. Reducing the solubility and hence mobility of the contaminant in groundwater or other fluids with which it is in contact.

4.2.1 Containment Technologies

Containment technologies for application at Superfund sites include capping, vertical barriers, and horizontal barriers. Since the selection of these containment technologies is not significantly influenced by the type of metal contaminant, and these technologies are already adequately addressed in the *Handbook for Stabilization Technologies for RCRA Corrective Actions* (EPA/625/6-91/026, August 1991); they are not discussed here. The Hydrologic Evaluation of Landfill Performance (HELP) computer program is available for computer analysis of landfill performance. The HELP program is an easy-to-use model that was developed to assist landfill designers and regulators by providing a tool to allow rapid, economical screening of alternative designs. HELP is a quasi-two-dimensional model that computes a daily water budget for a landfill represented as a series of horizontal layers. Each layer corresponds to a given element of a landfill design (e.g., cap, waste cell, leachate collection system, and liner). HELP considers a broad range of hydrologic processes including surface storage, runoff, infiltration, percolation, evapotranspiration, lateral drainage, and soil moisture storage (EPA/625/6-91/026, 1991).

TABLE 4-1. SOIL AND GROUNDWATER ACTION LEVELS AND RISK GOALS AT EXAMPLE SUPERFUND METAL-CONTAMINATED SITES

Region	Site Name/ Location/Type(a)	Contaminant/ Media	Initial Concentration	Cleanup Goal	Initial Risk	Final Risk
			ARSENIC			
2	Ringwood Mines Landfill, NJ Paint sludge disposal	As (GW)	57 ppb	50 ppb	(b)	(b)
3	Whitmoyer Laboratories, PA (OU-3 Final) Lab facility	As (soil)	No Data	21 mg/kg	No Data	No Data
4	Pepper's Steel and Alloys (OU-1 Final) Medley, FL General industrial area	As (soil)	1 to 200 mg/kg	5 mg/kg	No Data	No Data
7	Vogel Paint and Wax (OU-1 Final) Maurice, IA Paint waste disposal	As (soil)	4.8 to 65 mg/kg	Soil treatment will achieve leaching standards	1.7×10^{-4} total excess cancer	1×10^{-6} total excess cancer
10	Martin Marietta, OR (OU-1 Final) Aluminum manufacturing	As (soil)	No Data	65 mg/kg	10^{-4} to 10^{-1}	10^{-6}
			CADMIUM			
2	Waldick Aerospace (OU-1) Wall Township, NJ Aerospace parts manufacturing	Cd (soil)	< 16,200 mg/kg	3 mg/kg	No Data	No Data
3	Palmerton Zinc, PA (OU-1) Defoliated mountainside from zinc smelting	Cd (soil)	1,300 mg/kg	3 lb/acre	No Data	No Data
4	Independent Nail (OU-1) Beaufort, SC Electroplating	Cd (soil)	15 mg/kg	2.6 mg/kg	Inhalation 10^{-3}	10^{-6}
6	Pesses Chemical (OU-1 Final) Fort Worth, TX Reclamation of NiCad batteries	Cd (soil)	< 2,400 mg/kg	15 mg/kg	2×10^{-2}	1×10^{-6}
7	E.I. DuPont De Nemours (OU-1) West Point, IA Paint waste disposal	Cd (soil)	Not specified	20 ppm	No Data	No Data
			CHROMIUM			
1	Saco Tannery Waste Pits (OU-1 Final) Saco, ME Leather tannery wastes	Cr(VI) (soil) Cr(VI) (sediment)	2,625 mg/kg 2,297 mg/kg	375 mg/kg health-based target	5.6×10^{-6} (sediment absorption)	No Data
2	Genzale Plating Co. Franklin Square, NY Electroplating	Cr (soil)	37,300 mg/kg	6.7 mg/kg	No Data	No Data

TABLE 4-1. (continued)

Region	Site Name/ Location/Type[a]	Contaminant/ Media	Initial Concentration	Cleanup Goal	Initial Risk	Final Risk
CHROMIUM (cont)						
2	King of Prussia (OU-1) Winslow Twp., NJ Abandoned waste disposal facility	Cr (soil) Cr (GW)	< 11,300 mg/kg < 1,040 µg/L	483 mg/kg 50 µg/L	No Data	No Data
4	Bypass 601, NC (OU-1) Battery recycling facility and surrounding area	Cr (soil)	6.5 to 52 mg/kg	56 mg/kg	No Data	No Data
7	Vogel Paint and Wax (OU-1 Final) Maurice, IA Paint waste disposal	Cr(III) (soil)	4.9 to 21,000 mg/kg	Soil treatment will achieve leaching standards	1.7×10^{-4} total excess cancer	1×10^{-6} total excess cancer
LEAD						
2	Ringwood Mines Landfill, NJ (OU-1 Final) Paint Sludge Disposal	Pb (GW) Pb (soil)	85 ppb < 1300 mg/kg	50 ppb 250 mg/kg	[b]	[b]
3	Palmerton Zinc, PA (OU-1) Defoliated mountainside from zinc smelting	Pb (soil)	6,475 mg/kg	100 lb/acre	No Data	No Data
4	Bypass 601, NC (OU-1) Battery recycling facility and surrounding area	Pb (soil)	96 to 62,250 mg/kg	Excavate soil over 500 mg/kg and S/S to pass TCLP leach test	No Data	No Data
9	Beckman Instruments (OU-1 Final) Porterville, CA Manufacturer of electronic instruments	Pb (soil)	1,280 mg/kg	200 mg/kg	6×10^{-4} to 1.6×10^{-3}	No Data
MERCURY						
2	De Rewal Chemical (OU-1) Frenchtown, NJ Chemical Company	Hg (soil)	< 2.5 mg/kg	1 mg/kg	2×10^{-3}	1×10^{-4} to 1×10^{-7}
2	GE Wiring Devices (OU-1 Final) Puerto Rico Assembly of mercury switches	Hg (soil) Hg (GW)	ND to 62 mg/kg ND to 7,000 µ/L	16.4 or 21 mg/kg according to air monitoring	No Data	No Data
3	Saltville Waste Disposal Ponds, VA (OU-1) Chloralkali Plant	Hg (water)	10 to 120 µg/L	0.05 µg/L	No Data	No Data

TABLE 4-1. (continued)

Region	Site Name/ Location/Type[a]	Contaminant/ Media	Initial Concentration	Cleanup Goal	Initial Risk	Final Risk
		MERCURY (cont)				
2	King of Prussia (OU-1) Winslow Twp, NJ Abandoned waste disposal facility	Hg (soil) Hg (GW)	1.7 to 100 mg/kg Not detected	1 mg/kg 2 µg/L	No Data	No Data

(a) For more site information and implementation status, see Appendix D.
(b) Cleanup goals based on nonpromulgated New Jersey cleanup objectives.
(c) NJDEPE = New Jersey Department of Environmental Protection and Energy.
No Data = No data available in references as listed in Appendix D.

TABLE 4-2. TCLP LIMITS FOR METALS IN CHARACTERISTIC WASTES

			California	
EPA Hazardous Waste No.	Metal	TCLP Regulatory Limit (mg/L)	TTLC[a] (mg/L)	STLC[b] (mg/L)
D004	Arsenic	5.0	500	5.0
D005	Barium	100.0	–	–
D006	Cadmium	1.0	100	1.0
D007	Chromium	5.0	500	5.0
D008	Lead	5.0	1,000	5.0
D009	Mercury	0.2	20	0.2
D010	Selenium	1.0	100	1.0
D011	Silver	5.0	500	5.0

(a) Total Threshold Limit Concentration
(b) Soluble Threshold Limit Concentration

In addition to this document, there are a number of other EPA technical guides pertaining to containment technologies:

- *Lining of Waste Containment and Other Impoundment Facilities* (EPA/600/2-88-052), 1988
- Design, Construction, and Evaluation of Clay Liners for Waste Management Facilities (EPA/530/SW-86/007F), November 1988
- Technical Guidance Document: Final Covers on Hazardous Waste Landfills and Surface Impoundments (EPA/530-SW-89-047), July 1989
- Technical Guidance Document: Inspection Techniques for the Fabrication of Geomembrane Field Seams (EPA/530/SW-91/051), May 1991

- Technical Guidance Document: Construction Quality Management for Remedial Action and Remedial Design Waste Containment Systems (EPA/540/R-92/073), October 1992.

4.2.2 Solidification/Stabilization Technologies

Solidification and stabilization (S/S) methods of treating contaminated wastes are applied to change the physical or leaching characteristics of the waste or to decrease its toxicity. In the solidification process, waste constituents are physically locked within a solidified matrix in the form of a granular soil-like mixture or a monolithic block. Stabilization converts waste contaminants to a more immobile form, typically by chemical reaction. S/S refers to treatment processes that mix or inject treatment agents into the contaminated material to accomplish one or more of the following objectives:

- Improve the physical characteristics of the waste, without necessarily reducing aqueous mobility of the contaminant, by producing a solid from liquid or semiliquid wastes
- Reduce the contaminant solubility
- Decrease the exposed surface area across which mass transfer loss of contaminants may occur
- Limit the contact of transport fluids and contaminants

S/S treatment improves the waste handling or other physical characteristics of the waste and can reduce the mobility of contaminants. S/S treatment can be accomplished by treatment with inorganic binders such as cement, fly ash, and/or blast furnace slag or by organic binders such as bitumen.

S/S technology usually is applied by mixing contaminated soils or treatment residuals with a physical binding agent to form a crystalline, glassy, or polymeric framework surrounding the waste particles. In addition to the microencapsulation, some chemical mechanisms also may improve waste leach resistance. Other forms of S/S treatment rely on macroencapsulation in which the waste is unaltered but macroscopic particles are encased in a relatively impermeable coating.

4.2.2.1 In Situ and Ex Situ S/S

S/S can be either an in situ or ex situ process. The following descriptions of in situ and ex situ S/S are derived primarily from the Engineering Bulletin: *Solidification and Stabilization of Organics and Inorganics*, EPA/540/S-92/015, and the Engineering Forum Issue, *Considerations in Deciding to Treat Contaminated Unsaturated Soils In Situ*, EPA/540/S-94/500.

Ex situ processing involves: (1) excavation to remove the contaminated waste from the subsurface; (2) classification to remove oversize debris; (3) mixing; (4) off-gas treatment (if volatile, or dusts are present); and (5) a system for delivering the treated wastes to molds, surface trenches, or subsurface injection.

In situ treatment processing has only two steps: (1) mixing, and (2) off-gas treatment. The most significant challenge in applying S/S in situ for contaminated soils is achieving complete and uniform mixing of the binder with the contaminated matrix (U.S. EPA, 1990, EPA/540/2-90/002). Three basic approaches are used for in situ mixing of the binder with the matrix: (1) vertical auger mixing; (2) in-place mixing of binder reagents with waste by conventional earthmoving equipment, such as draglines, backhoes, or clamshell buckets; and (3) injection grouting, which involves forcing a binder containing dissolved or suspended treatment agents into the subsurface, allowing it to permeate the soil. Grout injection can be applied to contaminated formations lying well below the ground surface. The injected grout cures in place to produce an in situ treated mass.

4.2.2.2 Cement-Based S/S Technologies

This section describes application of inorganic stabilization materials, primarily Portland-type cements and siliceous pozzolans, for treatment of wastes contaminated with metals.

Description of Cement-Based S/S Technologies--

Cement-based S/S involves mixing contaminated materials with an appropriate ratio of cement or a similar binder/stabilizer and possibly water. The fundamental materials used to perform this technology are Portland-type cements and pozzolanic materials. Portland cements typically are composed of calcium silicates, aluminates, aluminoferrites, and sulfates. Pozzolans are very small spheroidal particles that are formed in combustion of coal (fly ash) and in lime and cement kilns, for example. Pozzolans of high silica content are found to have cement-like properties when mixed with water.

Inorganic binder systems using sodium silicate and cement/silicate systems are also used. Inorganic S/S treatment processes tie up free water by hydration reactions. Mobility of inorganic compounds can be reduced by formation of insoluble hydroxides, carbonates, or silicates; substitution of the metal into a mineral structure; sorption; physical encapsulation; and other mechanisms.

S/S treatment may involve using only Portland cement, only pozzolanic materials, or blends of both. The composition of the cement or pozzolan, together with the amount of water and aggregate added, determine set time, cure time, pour characteristics, and material properties of the resulting treated waste. For example, compressive strength is one physical property of the stabilized waste that is controlled by the composition variables. The compositions of cements and pozzolans, including those commonly used in S/S applications, are classified according to ASTM standards. Binder addition usually results in an increase in the treated waste volume.

A variety of additives are used with cement-based S/S treatment to assist in immobilizing specific contaminants or to improve physical characteristics. Activated carbon, organophilic clay, and other sorbents may be added to improve immobilization of organics. Soluble silicate additives are used to speed setting, reduce free water, and can precipitate lower solubility forms of some metals. Sulfide additions will provide reducing power and can form very low solubility metal sulfides.

Treatment Combinations with Cement-Based S/S Technologies--

Ex situ S/S is usually preceded by physical separation methods. Typically dry or wet screening is used to remove debris and produce a well-graded size distribution. The operations to load and mix waste and binder result in particulate air emissions. If the contaminated material contains organics, mixing operations and heating due to binder hydration will release organic vapors. Control of dust typically is needed and control of organic vapors may be needed in some applications. Pretreatment to change oxidation state (e.g., Cr reduction) or to moderate extreme pH may be needed.

For a waste containing metals and organics, pretreatment may be used to render the material more suitable for S/S. S/S treatment is not generally applicable to wastes with volatile organic compounds (VOCs) or high levels of semivolatile organic compounds (SVOCs). The waste can be prepared for S/S by techniques such as air stripping or incineration, depending on the type and concentration of the organics.

S/S treatment may be used as a pretreatment to improve the handling characteristics of a waste. For example, cement may be added to convert a sludge to a granular solid. Typical treatment combinations are shown in Table 4-3.

TABLE 4-3. TYPICAL TREATMENT TRAINS FOR CEMENT-BASED SOLIDIFICATION/ STABILIZATION TREATMENT AT METAL-CONTAMINATED SITES

Materials Handling	Pretreatment	Post-treatment/Residuals Management
Excavation	Screening for debris removal	Disposal of treated solid residuals (preferably below the frost line and above the water table)
Dredging	Size reduction for oversize material	
Conveying	Neutralization to moderate extreme pH	Containment barriers
	Reduction (e.g., Cr(VI) to Cr(III))	Off-gas treatment
	Oxidation (e.g., arsenite to arsenate)	
	Treatment to remove or destroy organics (e.g., incineration, soil washing, thermal desorption, bioremediation, or solvent extraction)	
	Physical separation to separate rich and lean fractions	

S/S of Cr(VI) requires reduction pretreatment as Cr(VI) is highly toxic and mobile in soils. Treatment consists of reducing Cr(VI) to the less toxic Cr(III), which is readily precipitated by hydroxide over a wide pH range.

Acidification followed by reduction and neutralization is a common approach to Cr reduction. Cr(VI) is a strong oxidizing agent under acidic conditions and thus converts to Cr(III) without strong reducing agents. Acidification can be accomplished using mineral acids. With the pH adjusted to <3, ferrous sulfate can be added to convert Cr(VI) to Cr(III). After chemical reduction, Cr(III) is precipitated by increasing the pH to >7 to coprecipitate chromium with ferric and ferrous iron (Conner, 1990).

Chemical treatments are also available for chromium reduction in neutral pH ranges. Possible chromium reduction reagents include sodium metabisulfite, sodium bisulfite, and ferrous ammonium sulfate (Jacobs, 1992). These reagents are more expensive than ferrous sulfate but may still be competitive in terms of overall costs. Reduction at neutral pH generates less sludge, so the potential waste volume is reduced (Conner, 1990).

In situ chemical treatment systems have the potential for introducing oxidizing, reducing, or neutralizing chemicals into the groundwater system, but chemical addition to the in situ environment may create a pollution problem in itself. Also, injection of treatment chemicals may create the requirement for land disposal. In such cases, the selection of reagents for chemical treatment will be limited by the Land Disposal Restrictions (LDRs) on introducing chemicals into the soil. In situ chemical treatment agents must be selected for compatibility with the environment. For example, in situ chromium-reducing sulfur is a possible candidate for acidification. Possible in situ chromium-reducing agents include leaf litter and acid compost (U.S. EPA, 1990, EPA/540/2-90/002). Formation of a crushed limestone barrier also has been proposed as an in situ chemical treatment method for Cr(III) (Artiole and Fuller, 1979).

Applicability of Cement-Based S/S Technologies--

If a single metal is the predominant contaminant in soil, sediment, or sludge, then cadmium and lead are the most amenable to cement-based S/S. The predominant mechanism for immobilization of metals in Portland and similar cements is precipitation of hydroxides. Both lead and cadmium tend to form insoluble hydroxides in the pH ranges commonly found in cement. They may resolubilize, however, if pH is not carefully controlled. Lead, for example, is subject to leaching and solubilization in the presence of even mildly acidic leaching solutions. At pHs around 10 and above, Pb tends to resolubilize as $Pb(OH)^{3-}$.

Metals (e.g., mercury) that do not have low solubility hydroxides, and species (e.g., Cr(VI), As(III) or As(V)) that exist as anions can be difficult to stabilize reliably (U.S. EPA, 1990, EPA/530-SW-90-059Q). Cement-based S/S is only applicable to low levels of mercury contamination (i.e., <260 mg/kg of Hg) because of failure to form low solubility hydroxides at high concentrations and is most applicable to elemental and inorganic forms of mercury. Also note that high volatility of mercury makes thermal recovery feasible at relatively low concentrations compared to other metals. Arsenic does not form insoluble hydroxides or carbonates and hence cement-based S/S does not apply for As. Arsenic sulfides may also have significant solubilities under the basic conditions typical of cement-based S/S. Cr(VI) is difficult to stabilize due to formation of cations that are soluble at high pH. Therefore, Cr(VI) is reduced to Cr(III), which does form insoluble hydroxides. Although cement-based S/S is difficult for Hg, As (III and V), and Cr (VI), this does not eliminate the possibility that effective S/S approaches will be identified for specific wastes containing these metals.

Wastes containing more than one metal are not addressed in this document other than to note that cement-based solidification/stabilization of multiple metal wastes will be particularly difficult if a set of treatment and disposal conditions cannot be found that simultaneously produces low mobility species for all the metals of concern. On the other hand, the various metal species in a multiple metal waste may interact (e.g. formation of low solubility compounds by combination of cationic and anionic metal species) to reduce the mobility of the contained metals. Appendix E includes multiple metal wastes for which S/S has been identified as RCRA BDAT. Figure 2 in Appendix A illustrates the variation in solubility of arsenate vs. pH and cationic metal species.

Organic contaminants are often present with inorganic contaminants at metal-contaminated sites. S/S treatment of organic-contaminated waste with cement-based binders is more complex than treatment of inorganics alone. Wastes in which organics are the primary contaminant of concern generally are not suited to S/S treatment. This is particularly true with VOCs where the mixing process and heat generated by cement hydration reaction can increase organic vapor losses (Ponder and Schmitt, 1991; Shukla et al., 1992; U.S. EPA, 1989, EPA/600/2-89/013; Weitzman and Hamel, 1990; U.S. EPA, 1990, EPA/9-90/006). However, S/S can be applied to wastes that contain lower levels of organics, particularly when inorganics are present and/or the organics are semivolatile or nonvolatile. Also, recent studies indicate that addition of silicates or modified clays to the binder system may improve S/S performance with organics (U.S. EPA, 1993, EPA/530/R-93/012).

S/S processes can be affected by the chemical constituents present in the waste being treated and by many other factors (e.g., binder-to-waste ratio, water content, or ambient temperature). The interferences caused by the chemical constituents of the waste can affect the solidification processes and/or the chemical stabilization of the treated product. Waste-specific treatability studies are needed to identify and overcome such interferences. General types of interference caused by the chemical constituents include (U.S. EPA, 1990, Treatability Study Protocol draft):

- Inhibition of bonding of the waste material to the S/S material
- Retardation of setting
- Reduction of stability of the matrix resulting in increased potential for leachability of the waste
- Reduction of physical strength of the final product.

Status and Performance of Cement-Based S/S Technologies--

Performance data of S/S measured in treatability studies were collected and analyzed by EPA. The results are summarized in Table 4-4. S/S with cement-based and pozzolan binders is a commercially available, established technology. Some transition metal salts, particularly Cu, Zn, and Pb, cause a pronounced retardation of the early hydration of calcium silicate cements (Thomas et al., 1981). The predominant mechanism for immobilization of metals in Portland and similar cements is precipitation of hydroxides. Metals (e.g., mercury) that do not have low-solubility hydroxides or species [e.g., Cr(VI), As(III), or As(V)] that exist as anions can be difficult to stabilize reliably (U.S. EPA, 1990, EPA/530-SW-90-059Q). A process to treat lead contamination by formation of anglesite ($PbSO_4$) and apatite ($(Ca_5CCl,F)(PO_4)_3$) has been accepted into the SITE Program (see Appendix B). As shown in Table 4-5, sites were identified where S/S has been selected for remediating of metal-contaminated solids. At 13 of these sites, S/S has been either completely or partially implemented. S/S is considered BDAT for lead and cadmium contaminated wastes. However, EPA does not preclude the use of S/S for treatment of As (particularly inorganic As) wastes, but recommends that its use be determined on a case-by-case basis. As shown in Table 4-5, there are five sites where As S/S is selected or implemented.

Only one NPL site, DeRewal Chemical, Frenchtown, New Jersey, was identified where S/S of a mercury bearing waste was selected, and the mercury concentration is less than 2.5 mg/kg. BDAT for non-wastewater >260 mg/kg Hg is acid leaching followed by chemical precipitation.

BDAT for chromium is chromium reduction and S/S. Cr(III) forms an insoluble hydroxide.

TABLE 4-4. GENERAL PROPERTIES OF RAW AND TREATED WASTES IN THE SUBSET OF THE TREATABILITY DATABASE

		Untreated Waste			
Metal	No. of Records[a]	Total Metal[b], mg/kg	Leachable Metal[c], mg/L	Ratio of Leachable to Total Metal[d], w/w	Reduction in Leachable Metal After Treatment, %
Arsenic	65	500 - 1,500	6.4 - 580	0.11 - 0.38	<0 - >99.9
Barium	5	NA[e]	400 - 1,100	NA	8.8 - >99.9
Cadmium	92	42 - 3,600	1.0 - 400	0.19 - 1.60	<0 - >99.9
Chromium	44	530 - 72,000	5.0 - 4,000	0.01 - 0.62	<0 - >99.9
Lead	280	110 - 670,000	5.2 - 3,400	0.01 - 1.40	<0 - >99.9
Mercury	15	NA	0.21 - 8.7	NA	33 - >99.9
Selenium	6	NA	3.1 - 97	NA	99.0 - 99.9
Silver	0	NA	NA	NA	NA

(a) Number of records remaining after leaching test and leachability criteria were applied. The full database contains many more records. There are multiple records for a single waste material if the treatability study tested more than one binder or binder-to-waste ratio.
(b) Total metal concentration was not reported for all records. Therefore, this range may not reflect full range for all samples.
(c) Leachable metal concentration was determined by EP, TCLP, or Cal WET test procedure.
(d) Ratio of leachable to total metal could not be calculated for records that did not include total metal concentration for untreated waste. Therefore, this range may not reflect full range for all samples.
(e) NA indicates not available.

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TABLE 4-5. SUMMARY OF SOLIDIFICATION/STABILIZATION SELECTIONS/APPLICATIONS AT SELECTED SUPERFUND SITES WITH METAL CONTAMINATION[a]

Region	Site Name/Location	Specific Technology	Key Metal Contaminants	Associated Technology	Status[b]
2	De Rewal Chemical, French Town, New Jersey	Solidification	Cr, Cu, Hg	GW pump and treatment	S
2	Marathon Battery Co., Cold Spring, New York	Chemical fixation (maectite process, pH 11-12)	Cd, Ni	Dredging, off-site disposal	I
2	Nascolite, Millville, Cumberland County, New Jersey	Stabilization	Pb	Off-site facility	S
2	Roebling Steel, Roebling, New Jersey	34-acre slag area	As, Cr, Pb	Capping	S
2	Waldick Aerospace, Wall Township, New Jersey	S/S 4,000 cy	Cr, Cd	LTTD, off-site disposal	C
3	Aladdin Plating, Clarks Summit, Pennsylvania	Stabilization 12,000 cy	Cr	Off-site disposal	C
3	Palmerton Zinc, Pennsylvania	Stabilization with fly ash, lime, potash	Cd, Pb, Zn	—	I
3	Tonolli Corp., Nesquehoning, Pennsylvania	S/S	As, Pb	In situ chemical limestone barrier	S
3	Whitmoyer Laboratories, Pennsylvania	Oxidation/fixation	As	GW pump and treatment, capping, grading, and revegetation	S
4	Bypass 601, North Carolina	S/S	Cr, Pb, Sb, Mn	Capping, regrading, revegetation, GW pump and treatment	S
4	Flowood, Mississippi	S/S 6,000 cy	Pb	Capping	C
4	Independent Nail, South Carolina	S/S	Cd, Cr, Ni, Zn	Capping	C
4	Pepper's Steel and Alloys, Medley, Florida	S/S	As, Pb	On-site disposal	C

(a) For more site information and implementation status, see Appendix D.

(b) Status codes: S = selected in ROD; I = in operation, not complete; C = completed.

TABLE 4-5. (continued)

Region	Site Name/Location	Specific Technology	Key Metal Contaminants	Associated Technology	Status[b]
6	Gurley Pit, Arkansas	In situ S/S	Ba, Pb, Zn	—	C
6	Pesses Chemical, Fort Worth, Texas	In situ S/S (12,400 cy)	Cd, Ni	Concrete capping	C
7	Vogel Paint and Wax, Maurice, Iowa	Stabilization	Cd, Cr(III), Pb, As, Hg, Ni, Zn	Biotreatment, GW pump and treatment	I
7	E. I. DuPont de Nemours, West Point, Iowa	S/S	Se, Cd, Cr, Pb	Capping, regrading, and revegetation	C
7	Mid-America Tanning, Sergeant Bluff, Iowa	In situ S/S	Cr, Pb	Capping, regrading, and revegetation	S
7	Shaw Avenue Dump, Charles City, Iowa	S/S	As, Cd	Capping, groundwater monitoring	C
10	Frontier Hard Chrome, Vancouver, Washington	Stabilization	Cr	—	S
10	Gould Site, Portland, Oregon	S/S	Pb	Capping, regrading, and revegetation	I

(a) For more site information and implementation status, see Appendix D.
(b) Status codes: S = selected in ROD; I = in operation, not complete; C = completed.

Estimated Costs of Cement-Based S/S Technologies--

The estimated cost of treating waste with S/S generally ranges from \$50 to \$250 per ton (1992 dollars). Costs are highly variable due to variations in site, soil, and contaminant characteristics. One report cites costs of in-drum, in-place, plant, and area mixing at \$512.80/yd^3, \$38/yd^3, \$41.80/yd^3, and \$43.50/yd^3, respectively. These costs include labor, equipment, monitoring and testing, reagents, and miscellaneous supplies. Not included are costs for equipment mobilization and demobilization, engineering and administration, and health and safety (Arniella and Blythe, 1990). Auger-type mixing systems developed by Novaterra (formerly Toxic Treatments USA); International Waste Technologies (IWT)/Geo-Con, Inc.; and S.M.W. Seiko, Inc. have been accepted for testing in the SITE Program. The reported cost for operation of a single auger machine is \$194/ton. Estimated cost for treatment operations using a four-auger machine of similar design was \$111/ton (U.S. EPA, 1991, EPA/540/5-91/008).

Note that some of the auger systems, particularly the Novaterra system, may inject steam (or steam and hot air) instead of binders to perform steam stripping of organics. Costs for S/S treatment developed from SITE Program Applications Analysis Reports are summarized in Table 4-6. Chemfix and Soliditech are ex situ treatment technologies. Cost modules for ex situ and in situ S/S with inorganic binders are available in the CORA model (see Appendix I).

TABLE 4-6. SOLIDIFICATION/STABILIZATION TREATMENT COST DATA

	IWT/Geo-Con(a) (In situ)		Hazcon(b) (In situ)		Chemfix(c) (Ex situ)	Soliditech(d) (Ex situ)
	4-Auger System (\$/ton)	1-Auger System (\$/ton)	300 lb/min 70% on Stream (\$/ton)	2,300 lb/min 70% on Stream (\$/ton)	37,000 tons(4) (\$/ton)	5020 yd^3 (\$/yd^3)
Site preparation	-	-	-	-	1.35	4.98
Permitting and regulatory	-	-	-	-	0.70	1.99
Equipment	34.35	87.64	12.93	7.91	5.00	12.56
Startup and fixed cost	3.71	1.52	2.31	2.31	0.89	4.18
Labor costs	16.56	46.18	65.02	8.57	27.00	49.98
Supplies - raw materials	52.68	52.68	116.67(1)	116.67(1)	30.00	62.53
Supplies – utilities	0.98	2.39	1.40	0.36	3.00	1.72
Effluent treatment	-	-	-	-	0.07	1.29
Residual transport	-	-	-	-	-	0.0(3)
Analytical	1.14	3.28	6.50	2.40	5.00	6.47
Facility modification	1.18	0.45	0.32	0.14	-	0.35
Demobilization	0.90	0.31	0.83	0.83	0.0(2)	2.99
Totals	111.50	194.45	205.98	139.19	73.01	149.04

- Not included in estimate.

(a) U.S. EPA. 1990. EPA/540/A5-89/004
(b) U.S. EPA. 1989. EPA/540/A5-89/001
(c) U.S. EPA. 1989. EPA/540/A5-89/011
(d) U.S. EPA. 1990. EPA/540/A5-89/005

(1) Conservative level of binder addition.
(2) Included in startup.
(3) On-site disposal.
(4) At a treatment rate of 160 tons per day.

Cement-Based S/S Technology Data Needs--

The data needs for S/S with cement-based treatment systems are presented in Table 4-7.

TABLE 4-7. SPECIFIC DATA NEEDS FOR SOLIDIFICATION/STABILIZATION CEMENT-BASED TREATMENT TECHNOLOGIES

Factor Influencing Technology Selection[a]	Conditions Favoring Success of S/S Treatment	Basis	Data Needs
Metal speciation	Not specified	Chemical form of metal determines its environmental behavior and likely reactions with treatment agents.	Measurement of different oxidation states of Cr and As.
pH and Eh: buffering capacity; apparent solubility of metals	Not Specified	pH and Eh can identify likely soluble species of metals (see Appendix A). Buffering capacity and apparent solubility can identify conditions leading to lowest solubility .	pH, Eh; neutralization potential; equilibration with pH and Eh controlled solutions.
Leachability	Depends on site cleanup goals	Metals need to remain immobile under expected disposal conditions as the treated materials age.	TCLP for regulatory purposes only. Equilibrium and/or diffusion-controlled leach tests that mimic expected post-treatment disposal conditions.
Organic content	<20 to 45 wt% total organic content	Organic materials can interfere with bonding	Analysis for VOCs and total organic carbon (TOC)
VOC content	<50 ppb	VOCs can vaporize during process or curing. Organic materials can interfere with bonding	Analysis for VOCs
SVOC content	organics <10,000 ppm PAHs <10,000 ppm	Organic materials can interfere with bonding	Analysis for SVOCs and polycyclic aromatic hydrocarbons (PAHs)
Oil and grease content	<10 wt% total oil and grease content	Oil and grease coat the waste particles and weaken the bond between the waste solids and cement	Analysis for oil and grease
Phenol content	<5%	Phenols can reduce compressive strength of final product	Analysis for phenol
Particle size	Limited amount of insoluble particulate passing through a 200 mesh screen	Fine particulate can coat the waste particles and weaken the bond between the waste solids and cement	Particle-size distribution
Halide content	Not specified	Presence of halide salts can alter cement setting rate. Halides generally are soluble and can leach from cement.	Analysis for total halides
Soluble salts of manganese, tin, zinc, copper, and lead content of the waste	Not specified	Soluble salts of these metals can reduce the physical strength of the final product, cause large variations in setting time, or reduce the dimensional stability of the cured matrix	Analysis of inorganic content
Cyanide content	<3,000 mg/kg	Cyanides interfere with bonding of waste materials	Analysis for cyanides
Sulfate content	<1,500 ppm for Type I Portland cement Cements can be formulated to tolerate higher sulfate levels	Retards setting Can cause cement to spall after curing	Analysis for sulfate

TABLE 4-7. (continued)

Factor Influencing Technology Selection[(a)]	Conditions Favoring Success of S/S Treatment	Basis	Data Needs
Ability to obtain good mixing of waste particles and binder	Not specified	Cement must coat particles to obtain a good S/S product	Waste particle-size distribution Waste moisture content Waste viscosity
Binder heat of hydration	Not specified	Heat generation, particularly in large mass treatment, can increase temperature and volatilize organic and metal contaminants	Total and time-dependent heat output of binder formulation
Moisture content	Not specified	Quantify the amount of water addition/ removal needed for S/S mixing process	Waste moisture content
Unconfined compressive strength	Treated waste usually requires 50 psi, but higher levels may be needed. Must exceed intended use limits.	Evaluate changes in response to overburden stress between treated and untreated waste	Unconfined compressive strength of treated and untreated waste
Flexural strength	Not specified, must exceed intended use limits	Evaluate material's ability to withstand loads over large areas	Treated waste flexural strength
Cone index	Not specified, must exceed intended use limits	Screening test for material compressive strength	Cone penetrometer test
Durability testing	Not specified, must exceed intended use limits	Evaluate durability of treated waste	Treatability test Freeze-thaw cycling tests Wet-dry cycling tests
pH	Not specified. Treated waste pH range about 9.0 to 11.5 required for setting (cement hydration) and to minimize metal solubility.	Evaluate changes in leaching as a function of pH Develop binder formulation	pH of untreated and treated waste
Alkalinity	Not specified. Treated waste pH range about 9.0 to 11.5 required for setting (cement hydration) and to minimize metal solubility.	Evaluate changes in leaching as a function of pH Develop binder formulation	Alkalinity of untreated and treated waste
Volume increase following treatment	Minimum volume increase consistent with effective binder addition. Most critical when disposal site space is limited or long distance, off-site disposal is planned.	Increased treated waste volume increases cost of transportation, disposal, and disposal area/volume/surface topography	Density and volume before and after treatment based on treatability testing

TABLE 4-7. (continued)

Factor Influencing Technology Selection[(a)]	Conditions Favoring Success of S/S Treatment	Basis	Data Needs
		For In Situ	
Subsurface conditions	Not specified	Presence of subsurface barriers or debris Depth to first confining layer	Subsurface geology Waste conditions
Contaminant depth	Varies with technology	In-place mixing limited to near surface. Auger systems demonstrated to 30 feet. With newly developed equipment, treatment to 150 feet should be possible	Waste composition and spatial distribution

(a) Use hazardous substance list and site historical records to plan total waste analysis

Source: Adapted from Arniella and Blythe, 1990; Conner, 1990; McGrail and Olson, 1992; U.S. EPA, 1988, EPA/540/2-88/004; U.S. EPA, 1990, EPA/540/2-90/002; U.S. EPA, 1991, EPA/540/2-91/009; U.S. EPA, 1993, EPA-823-B93-001; and U.S. EPA, 1993, EPA/530/R-93/012.

4.2.2.3 Polymer Microencapsulation

This subsection describes application of asphalt and similar organic binders to treatment of wastes contaminated with metals or with metals and organics.

Description of Polymer Microencapsulation Technologies--

S/S by polymer microencapsulation can include application of thermoplastic or thermosetting resins. Thermoplastic materials are the most commonly used organic-based S/S treatment materials. Potential candidate resins for thermoplastic encapsulation include bitumen, polyethylene and other polyolefins, paraffins, waxes, and sulfur cement. Of these candidate thermoplastic resins, bitumen (asphalt) is the least expensive and by far the most commonly used (Arniella and Blythe, 1990). The urea-formaldehyde thermosetting resin systems experienced limited use in the solidification of low-level radioactive waste. This application has been discontinued due to poor performance of the system. Research is continuing on other thermoset resins for waste encapsulation (Weingardt, 1993).

The process of thermoplastic encapsulation involves heating and mixing the waste material and the resin at elevated temperature, typically 130°C to 230°C, in an extrusion machine. Any water or volatile organics in the waste boil off during extrusion and are collected for treatment or disposal. Because the final product is a stiff, yet plastic resin, the treated material typically is discharged from the extruder into a drum or other container. Asphalt-treated soils or abrasives contaminated with metals have been reused as paving material (Means et al., 1993).

Treatment Combinations With Polymer Microencapsulation Technologies--

As with cement-based S/S, polymer microencapsulation typically requires physical separation to remove debris and condition the particle-size distribution of the feed. In addition, wet feed materials must be dried. Typical treatment combinations are shown in Table 4-8.

TABLE 4-8. TYPICAL TREATMENT TRAINS FOR POLYMER MICROENCAPSULATION TREATMENT AT METAL-CONTAMINATED SITES

Materials Handling	Pretreatment	Post-treatment/Residuals Management
Excavation	Screening for debris removal	Disposal of treated solid residuals (preferably below the frost line and above the water line)
Dredging	Size reduction for oversize material	Containment barrier
Conveying	Dewatering for wet sludge	Reuse for onsite paving
	Drying	Air pollution control
	Physical separation to separate rich and lean fractions	

Applicability of Polymer Microencapsulation Technologies--

Organic binder systems have been used mainly to treat low-level radioactive wastes. However, organic binders have been tested or applied to wastes containing chemical contaminants such as arsenic, metals, inorganic salts, PCBs, and dioxins (Arniella and Blythe, 1990). Organic binder systems function mainly by physical encapsulation in the water-insoluble organic resin. Polymer micro-encapsulation is particularly well suited to treating water-soluble salts such as chlorides or sulfates that generally are difficult to immobilize in a cement-based system (Kalb, Holmes-Burns, and Meyer, 1993).

Characteristics of the organic binder and extrusion system impose compatibility requirements on the waste material. The elevated operating temperature places a limit on the quantity of water and VOCs in the waste feed. Less volatile organics will be retained in the bitumen but may act as solvents causing the treated product to be too fluid. The bitumen is a potential fuel source so the waste should not contain oxidizers such as nitrates, chlorates, or perchlorates. Oxidants present the potential for rapid oxidation, causing immediate safety concerns as well as slow oxidation that results in waste form degradation.

Status and Performance of Polymer Microencapsulation Technologies--

S/S with organic binders requires more complex equipment and operations and higher energy use than cement-based stabilization. Applications have been limited to special cases where the specific performance features are required or the waste matrix and contaminants allow reuse of the treated waste as a construction material (Means et al., 1993, ASTM).

Estimated Cost of Polymer Microencapsulation Technologies--

The general cost elements for a thermoplastic microencapsulation system are shown in Table 4-9.

Polymer Microencapsulation Technologies Data Needs--

The data needs for organic encapsulation technologies are shown in Table 4-10.

TABLE 4-9. ESTIMATED TOTAL PROJECT COSTS FOR MICROENCAPSULATION OF SOILS CONTAMINATED WITH METALS ONLY OR WITH VOCs AND METALS

Item	Case 1 10,000 TPY (Dollars)	Case 2 100,000 TPY (Dollars)
Capital (Includes Transportation and Installation)		
Heated Screw Dryer (for Drying and Stripping VOCs)	669,000	1,630,000
Extruder (for Mixing Soil and Asphalt)	488,000	1,200,000
Soil Screening, Conveying, Handling, and Other Ancillary Equipment	343,000	670,000
Subtotal	1,500,000	3,500,000
Operations and Maintenance		
Labor	1,450,000	1,870,000
Equipment Rental	400,000	685,000
Raw Materials and Major Utilities	1,800,000	16,945,000
Subtotal	3,650,000	19,500,000
Technology Implementation		
Designs, Plans, Specifications, and Regulatory Approval (20% of Capital)	300,000	700,000
Contingency at 25% of Summed Up Costs for Capital, O&M, and Implementation	1,360,000	5,925,000
Total Project Cost	**6,810,000**	**29,625,000**

Notes:

Total project cost assumes single use and operation for 1 year.
No salvage/reuse value has been attributed to the equipment.
TPY = tons per year.

Source: Roy F. Weston, Inc., 1987.

4.2.3 Vitrification Technologies

This subsection describes technologies that apply high-temperature treatment aimed primarily at reducing the mobility of metals by incorporation in a vitreous mass. These technologies also vaporize or destroy organic contaminants in addition to immobilizing the metals in a stable oxide solid. More details on vitrification technologies for treatment of hazardous waste are given in an EPA handbook (U.S. EPA, 1992, EPA/625/R-92/002). High-temperature processing to recover metals is discussed in Subsection 4.3.1.3.

4.2.3.1 Vitrification of Excavated Materials

This section describes application of vitrification to treatment of excavated wastes contaminated with metals or with metals and organics.

TABLE 4-10. SPECIFIC DATA NEEDS FOR POLYMER MICROENCAPSULATION TECHNOLOGIES

Factor Influencing Technology Selection[a]	Basis
Water content	The processes usually require a dry solid feed so drying would be needed to prepare a high-moisture-content waste
Presence of oxidizing agents such as nitrates, chlorates, or perchlorates	Organic binder is a potential fuel source and may react violently with oxidizers Oxidizers will cause slow deterioration of the binder
Presence of organic solvents	Organic solvents, particularly aromatic solvents, can dissolve the binder
Presence of oils, greases, and chelating agents	Oils, greases, and chelating agents will dissolve in and migrate through the binder Oils, greases, and chelating agents can coat the waste particles, thus preventing a good bond with the binder
Presence of thermally unstable materials	Hydrated salts can decompose during hot mixing with the binder, thus liberating vapor and causing poor bonding

(a) Use hazardous substance list and site historical records to plan total waste analysis

Source: Adapted from U.S. EPA, 1991, Treatment Technology Background.

Description of Technologies for Vitrification of Excavated Materials--

The vitrification process can incorporate oxides of nearly all the elements of the periodic table. With the addition of low-cost materials such as sand, clay, and/or native soil, the process can be adjusted to produce products with specific characteristics, such as chemical durability. Waste vitrification may be able to transform the waste into useful, recyclable products such as clean fill, aggregate, or higher valued materials such as erosion control blocks, paving blocks, and road dividers. The vitrification process can accommodate different chemical and physical forms of matter including liquids, slurries, sludges, combustible or noncombustible solids, and mixtures of these physicochemical states, making vitrification an attractive method of waste treatment because a single technology can process widely different materials. Vitrification, or making glass out of wastes, treats waste by destroying organic materials and immobilizing metals and radioactive elements into a chemically durable, leach-resistant solid. Due to the melting and densification of minerals, combustion or volatilization of organics, and vaporization of water, the glass product from vitrification occupies less volume than the waste feed.

Energy input to form the glass melt is one of the significant cost elements in vitrification. Soil is a typical material requiring treatment at CERCLA sites. The theoretical heat required to melt various commercial glasses is presented in Table 4-11. These energy requirements indicate an approximate minimum for glass formation. The actual energy requirements for vitrification of waste must be corrected for process losses and for the water content and exothermic energy sources present in the feed. The theoretical energy requirements for melting dry oxides or soil range from 560 to 680 kW-hr/ton. Process heat losses may increase heat requirements significantly when the throughput is below 10 tons/day. An electrical resistance vitrification remediation process that operates near commercial glass production rates would require an energy input of about 800 kWh/ton. Materials, such as organics, that release energy on oxidation will reduce energy input requirements. For waste with more than ~18 dry wt% carbon, the electrical power requirements can be less than 100 kW-hr/ton because oxidation of the carbon near the molten glass surface provides much of the energy needed to melt the accompanying ash or soil. Depending on the local energy costs, different sources of energy can be used to minimize costs. For example, coal can be added to contaminated soil to lower costs using its oxidation near the molten glass interface to offset the electrical cost.

TABLE 4-11. THEORETICAL ENERGY INPUTS REQUIRED TO FORM VARIOUS GLASS TYPES

	Soda-lime, Container Glass	Borosilicate, Laboratory Glass	Lead Crystal Glass
Heat of Reaction, kJ/kg	487	412	403
Enthalpy (20 to 1500°C), kJ/kg	1,886	1,701	1,693
Batch gases (20 to 1500°C), kJ/kg	289	138	164
Theoretical Total, kJ/kg	**2,662**	**2,251**	**2,260**
Theoretical Total, kcal/kg	636	538	540
Theoretical Total, btu/kg	2,524	2,134	2,142
Theoretical Total, kWh/kg	0.740	0.626	0.628
Theoretical Total, btu/#	1,147	970	974
Theoretical Total, kWh/#	0.336	0.284	0.286
Theoretical Total, kWh/ton	673	569	571

In fossil, fuel-heated, glass melters with concurrent flow of waste and combustion gases, a substantial quantity of energy is lost to the off-gas system. For example, a conventional fossil-fueled, 100 ton/day glass melter that uses recuperators for efficiency consumes about 1,570 to 1,770 kWh/ton of glass produced.

Typical Treatment Combinations with Technologies for Vitrification of Excavated Materials--

The stages in the complete remediation process may include waste excavation, pretreatment, mixing, feeding, melting, off-gas cleanup, recycle of filtered off-gas material, and casting or forming of the discharged melted material. Most of the vitrification systems do not require any pretreatment operations. Those melter technologies that do require pretreatment typically are limited to size reduction. However, pretreatment operations also may include drying, desorption, segregation of metal components, and size reduction of the material. Volatile metals can be difficult to retain during the vitrification process. Arsenic is more volatile in some forms than in others. For example, arsenic oxide may be more volatile than calcium or iron arsenates. Certain waste feeds may require chemical or thermal pretreatment to convert arsenic oxide to less volatile forms before vitrification (U.S. EPA, 1992, EPA/625/R-92/002).

Off-gas cleanup systems are more strongly dependent upon the waste being treated than on the vitrification process. If the organic content is relatively high, an afterburner may be required to guarantee the destruction of escaping organics. The balance of the off-gas system will be directed toward gas quenching, acid gas scrubbing, and removal and recycle of particulates. Typical treatment combinations are shown in Table 4-12.

Applicability of Technologies for Vitrification of Excavated Materials--

Vitrification can treat a wide variety of mixed organic and inorganic contaminants in slag, soil, and sludge wastes. Organics are destroyed by pyrolysis and combustion. Metals are incorporated in a leach-resistant matrix. When the silica content of the waste is sufficient to form glass with minimal additions, the waste volume can be reduced. Despite these advantages, vitrification is not widely used. The technology is expensive to implement and the current commercially available capacity for hazardous waste vitrification is limited.

TABLE 4-12. TYPICAL TREATMENT TRAINS FOR EX SITU VITRIFICATION TREATMENT AT METAL-CONTAMINATED SITES

Materials Handling	Pretreatment	Post-treatment/Residuals Management
Excavation	Screening for debris removal	Disposal of treated solid residuals (preferably below the frostline and above the water table)
Dredging	Size reduction for oversize or refractory material	
Conveying	Dewatering for wet sludge	Reuse as construction aggregate
	Drying	Air pollution control
	Physical separation to separate contaminant-rich and contaminant-lean fractions	
	Conversion of metals to less volatile forms [e.g., As_2O_3 to $Ca_3(AsO_4)_2$]	

For successful treatment by vitrification, the metals must be retained in the melt during heating and incorporated into the vitrified mass that forms as the melt cools. The melt is formed under oxidizing conditions so metals will tend to convert to oxides, silicates, or other compounds with high boiling points. Metals retained in the melt must be solubilized to minimize formation of crystalline phases that can decrease the leach resistance of the vitrified product. The approximate solubility limits of some elements in silicate glasses are shown in Table 4-13. These are only rough guidelines of the limits for incorporation of the elements into the vitrified waste. The actual solubility depends on the waste matrix and glass formulation. As an approximation for starting melt formulation, the waste concentration should be adjusted with soil or other silica sources to decrease each metal below its solubility limit. Keeping the metal below the solubility limit helps ensure melt homogeneity and helps avoid accumulation of refractory sludges in the melter.

TABLE 4-13. APPROXIMATE SOLUBILITY OF ELEMENTS IN SILICATE GLASSES

Solubility	Elements
Less than 0.1 wt%	Ag, Ar, Au, Br, H, He, Hg, I, Kr, N, Ne, Pd, Pt, Rh, Rn, Ru, Xe
Between 1 and 3 wt%	As, C, Cd, Cr, S, Sb, Se, Sn, Tc, Te
Between 3 and 5 wt%	Bi, Co, Cu, Mn, Mo, Ni, Ti
Between 5 and 15 wt%	Ce, F, Gd, La, Nd, Pr, Th, B, Ge
Between 15 and 25 wt%	Al, B, Ba, Ca, Cs, Fe, Fr, K, Li, Mg, Na, Ra, Rb, Sr, U, Zn
Greater than 25 wt%	P, Pb, Si

Source: Adapted from U.S. EPA, 1992, EPA/625/R-92/002.

Most of the high-temperature immobilization technologies rely on the natural corrosivity of the molten material and conductive heat transfer to dissolve the waste matrix and contaminants. The particle size of the waste may need to be controlled for some of the different melting technologies. For wastes containing refractory compounds that melt above the unit's nominal processing temperature, such as quartz or alumina, size reduction may be required to achieve reference throughputs and a homogeneous melt. Size reduction is not a major factor for the high-temperature processes using arcing or plasma technologies. For the intense melters using concurrent gas-phase melting or mechanical agitation, size reduction is needed for feeding the system and for achieving a homogeneous melt.

Several melting technologies are being tested or applied to the treatment of nonhazardous, hazardous, radioactive, and mixed radioactive and hazardous wastes. The melting technologies may be grouped into two general categories: melters that provide either long or short residence time in the molten state. Within these two categories are a wide range of specific process designs. The designs are aimed at optimizing cost and performance, particularly by reducing capital and energy costs for the melter. Different melter configurations and melt homogenization methods are used. Heat can be applied through a variety of sources such as combustion of fossil fuels (coal, natural gas, and oil) in the melter or input of electric energy by direct joule heating, arcing, plasma torches, and microwaves. Combustion or oxidation of the waste can contribute significant energy to the melting process.

Barium, beryllium, chromium, copper, nickel, silver, thallium, and zinc typically will be incorporated into the oxide melt, particularly if recycle from the off-gas system is practiced. Arsenic, lead, and selenium also will be incorporated but with more difficulty, particularly for co-current fossil fuel-fired designs. Chlorides present in the waste in excess of about 0.5 wt % typically will not be incorporated into and discharged with the glass, but will fume off and enter the off-gas treatment system. If chlorides are excessively concentrated, salts of alkali, alkaline earths, and heavy metals will accumulate in solid residues collected by off-gas treatment. Separation of the chloride salts from the other residuals may be required before or during return of residuals to the melter.

Status and Performance of Technologies for Vitrification of Excavated Materials--

A number of hazardous waste vitrification systems are under development. Characteristics of some example vitrification technologies are summarized in Table 4-14.

TABLE 4-14. SUMMARY OF EX SITU VITRIFICATION TECHNOLOGIES FOR METAL-CONTAMINATED WASTE

Vendor/Technology	Testing Sites	Tested Contaminant and Matrix	Scale of Operation	Energy Consumption
		Long-Residence-Time Melters		
EM&C Engineering Associates Vitriflux	Costa Mesa, CA	Metal-bearing sludge and slag	Bench-scale[(c)]	Electrical resistance heating
Envitco Cold-Top Melter	Sylvania, OH	Metal-bearing ash and radioactive waste	Pilot-scale (transportable)	Electrical resistance heating
Ferro Corporation[(a)]	Independence, OH	Synthetic soil matrix spiked with metals	Bench-scale	Electrical resistance heating
Glassification International	Steel mill in the Pacific Northwest	K061 electric arc furnace dust	Pilot-scale	Electrical resistance heating
Penburthy Electromelt, Inc. Penburthy glass melter	Seattle, WA	RCRA organics and inorganics	Full-scale (50 tons per day)	Electrical resistance heating 1,000 kWh/ton
Terra-Vit	Richland, WA	No data available	No data available	Electrical resistance heating
Vitrifix, England	Faslane, England	Asbestos-contaminated soils	Full-scale	Electrical resistance heating

TABLE 4-14. (continued)

Vendor/Technology	Testing Sites	Tested Contaminant and Matrix	Scale of Operation	Energy Consumption
Short-Residence-Time Melters				
Allis Mineral Systems Pyrokiln Thermal Encapsulation[a]	Oak Creek, WI	Metal-bearing slags and sludges	Bench-scale testing performed Pilot-scale equipment available	Fossil fuel heating
Ausmelt Sirsomelt	Denver, CO	Metal-bearing slags and sludges	Pilot-scale (in US) Full-scale (in Australia)	Fossil fuel heating
B&W - Nuclear Cyclone Furnace[a]	Alliance, OH	Synthetic soil matrix spiked with metals	SITE Demonstration	Fossil fuel heating
EET Corp. Microwaste Melter[b]	Rocky Flats, CO	Metal-bearing sludge	Pilot-scale	Microwave energy supply
Electropyrolysis	Wayne, PA	Metal-bearing sludge	Pilot-scale[c]	Electric arc heating
Plasma Energy Corp. Plasma Arc Furnace	Several	High hazard materials such as radioactive or medical waste	Bench-scale with plans for pilot scale.	Plasma arc heating 270 kWh/ton
Retech, Inc. Plasma Centrifugal Reactor[a][b]	Butte, Montana	Soil from Silver Bow Creek Superfund site spiked with zinc oxide, hexachlorobenzene, and oil	Pilot-scale	Plasma arc heating 21,800 to 7,260 kWh/ton
Stir-Melter, Inc Stir-Melter	Toledo, OH	Simulated radioactive waste, fly ash, fiber glass	Full-scale	Electrical resistance heating
Vortec Corp. Advanced Vitrification/Incineration Process[a][b]	Harmarville, PA	Soil contaminated with metals, Wastewater treatment incinerator ash, municipal solid waste (MSW) fly ash, and hazardous baghouse dust	Pilot-scale	Fossil fuel heating
Westinghouse Electric Corp. Plasma Cupola Process	Pittsburgh, PA	Steel mill wastes, simulated landfill material, PCB-contaminated waste	Full-scale	Plasma arc heating 1,000 to 1,180 kWh/ton
Western Product Recovery Group Coordinate, Chemical Bonding and Adsorption[a][b]	Houston, TX	Soils contaminated with metals and organics	Pilot-scale test planned	Fossil fuel heating

(a) SITE Program Technology, see Appendix B.
(b) Listed in VISITT, see Appendix C.
(c) Both ex situ and in situ implementations in development.

Sources: U.S. EPA, 1992, EPA/540/R-92/077; Roy F. Weston, 1987, AMXTH-TE-CR-86101; U.S. EPA, 1992, EPA/540/AR-92/017; U.S. EPA, 1993, EPA/542-R-93-001.

Estimated Costs of Technologies for Vitrification of Excavated Materials--

The challenge in vitrification is to process wastes at competitive costs. Treatment costs for vitrification are highly dependent on the waste, throughput capacity, local energy costs, and site location. The dominant costs for conventional glass melters are capital recovery and labor. Energy costs can be reduced by mixing solid waste fuels such as waste wood, tires, and/or low-grade coal. Detailed analysis of cost elements for vitrification is presented in U.S. EPA (1992, EPA/625/R-92/002).

The Babcock & Wilcox cyclone furnace was evaluated under the SITE Program. Cost estimates reported in the Applications Analysis Report are given in Table 4-15 (U.S. EPA, 1992, EPA/540/AR-92/017). The effect on various factors of the total amount of material processed is shown. The cost estimates assume that a 3.3-ton/hr furnace operates 60% of the available time. Estimates are based on transporting and setting up a furnace at a generic site 1,000 miles from Alliance, Ohio.

TABLE 4-15. TREATMENT COSTS FOR A 3.3-TON/HR BABCOCK & WILCOX CYCLONE VITRIFICATION FURNACE WITH A 60% ONLINE FACTOR

	Cost for Various Total Throughputs ($/ton)		
Cost Element	10,000 Tons Total Throughput	20,000 Tons Total Throughput	100,000 Tons Total Throughput
Site preparation	31.37	31.37	31.37
Permitting and regulatory costs	n/r	n/r	n/r
Equipment cost incurred	50.46	43.83	38.53
Startup and fixed costs	109.90	58.67	17.69
Labor	219.95	219.95	219.95
Supplies	2.02	2.02	2.02
Consumables	157.96	157.96	157.96
Effluent treatment and disposal	n/r	n/r	n/r
Residuals shipping, handling, and transport	n/r	n/r	n/r
Analytical costs	n/r	n/r	n/r
Facility modification, repair, and replacement	1.24	1.24	1.24
Site demobilization	27.67	13.83	2.77
Total operating costs	600.57	528.88	471.53

(a) Includes transportation and setup on site.
n/r = Not included in cost estimate.

Source: U.S. EPA, 1992, EPA/540/AR-92/017.

Data Needs for Vitrification of Excavated Materials Technology--

The data needs for vitrification of excavated materials are shown in Table 4-16.

TABLE 4-16. SPECIFIC DATA NEEDS FOR VITRIFICATION TECHNOLOGIES APPLIED TO EXCAVATED MATERIALS

Factor Influencing Technology Selection[(a)]	Conditions Favoring Success of Treatment	Basis	Data Needs
Silica and alkali content	>30% SiO_2 >1.4% alkali on dry weight basis	Required to form melt and cool to stable treated waste form. Can be adjusted by frit addition.	Waste matrix analysis
Particle size	Varies with technology	Preprocessing usually required to ensure particle size is compatible with feed system and melter heat transfer	Material particle-size distribution
Moisture content	<25% water by weight	Energy input is required to vaporize water	Waste moisture content
Metal content	See Table 4-13	Most metal oxides have solubility limits in glass matrices	Waste composition
Waste organic content	<10%	Increases off-gas volume (not applicable to fossil-fueled systems)	Organic analysis Weight loss on ignition
Volatile metals	Not specified	Volatile metals such as mercury and cadmium may exist in off-gas, thus requiring special treatment of off-gas	Complete inorganic characterization (cations)
Power availability	Adequate utility supply available	Vitrification requires significant energy input	Local infrastructure
Sulfates, sulfides, chlorides, and fluorides	Not specified	Sulfates and chlorides can react to form volatile metal species or corrosive acids	Complete inorganic characterization (anions)
Mineral content	Not specified	Mineral content can affect glass viscosity, corrosivity, and other properties	Weight loss on ignition Weight fraction of metals as oxides

(a) Use hazardous substance list and site historical records to plan total waste analysis.

Source: Adapted from U.S. EPA, 1988, EPA/540/2-88/004 and U.S. EPA, 1991, *Treatment Technology Background.*

4.2.3.2 Vitrification of In Situ Materials

This subsection describes the application of vitrification to in situ materials for the treatment of wastes contaminated with metals or with metals and organics.

Description of Technologies for Vitrification of In Situ Materials--

Vitrification in situ is a thermal treatment process that converts contaminated soils to a stable glass and crystalline monolith. The in situ vitrification (ISV) technology is based on electric melter technology, and the principle of operation is joule heating, which occurs when an electrical current is passed through a region that behaves like a resistive heating element. Electric current is passed through the soil through an array of electrodes inserted vertically into the surface of the contaminated soil zone. Because dry soil is not conductive, a starter path of flaked graphite and glass frit is placed in a small trench between the electrodes to act as the initial flow path for electricity. Resistance heating in the starter path transfers heat to the soil, which then begins to melt. Once molten, the soil becomes conductive. The melt grows outward and downward as power is gradually increased to the full constant operating power level. A single melt can treat a region of up to 1,000 tons. The maximum treatment depth has been demonstrated to about 20 feet. Large contaminated areas are treated in multiple settings which fuse the blocks together to form one large monolith.

During the ISV process, organic wastes are pyrolyzed as they are thermally contacted by the melt front, while inorganics are incorporated into the vitreous mass. Off-gases released during the melting process, containing volatile components and products of combustion and pyrolysis, are confined in a steel off-gas hood placed over the site being treated. The off-gas is directed to a series of wet scrubbers, dry filters, and adsorption units where it is treated before being released to the atmosphere (Buelt et al., 1987). The water from the off-gas treatment system can be treated and re-used, while solid residuals from the off-gas treatment system (e.g. activated carbon, filters, sludges) can be vitrified in a subsequent batch. Thus, only residuals from the last vitrification setting at the site need to be discarded. (U.S. EPA, 1994, EPA/540/S-94/504)

Bio-Electrics, Inc. has also developed a technology for ISV of contaminated soil by electro-gasification. The process depends on the electrical conductivity of earth strata (electrolytic conductivity) and induced conductivity generated by electropyrolysis of hydrocarbons. This technology consists of several steps:

1. Hydrofracturing the soil.
2. Injecting electrically conductive propants into bedrock fractures. Propants are materials that can be used to fill the fracture to prevent it from collapsing. A typical propant is coarse sand.
3. Applying electric energy through electrodes placed in wells and injecting air simultaneously for fusing of solid material.
4. Recovering the off-gas through electrode wells (U.S. EPA, 1993, EPA/542-R-93-001).

Typical Treatment Combinations With Technologies for In Situ Vitrification--

ISV technology should require little or no pretreatment or post-treatment in many instances. Exceptions include: shallow (< 5 to 7 feet) soils, in which it is advantageous to stage into deeper trenches; wet soils, for which dewatering may be necessary to reduce energy costs, steam formation, and movement of contaminants into groundwater. Also, as noted in the preceding section, off-gasses are generated and require treatment, but to the extent that the offgas contaminants are re-incorporated into the vitrified waste, off-gas residuals requiring post-vitrification treatment are limited to those from the last melt. (U.S. EPA, 1994, EPA/540/S-94/504).

Applicability of Technologies for Vitrification of In Situ Materials--

ISV is applicable to contaminated sludges and soils regardless of whether they are sand, silt, or clay. However, special monitoring and/or analyses must be performed when melting silty soils or nonswelling clays due to their low permeabilities (Buelt and Thompson, 1992). ISV is applicable to soils containing a combination of hazardous organic and inorganic contaminants. High concentrations of combustible debris, concrete rubble, rock, and scrap metals are all processible by ISV; however, containers such as tanks and drums must not be present. Volatile contaminants (e.g., mercury, arsenic, or organics) may be difficult to capture and treat effectively or may migrate through the subsurface. Implementation costs are high (Buelt and Thompson, 1992).

The main requirement for the technology is the ability for the soil melt to carry current during heating and then solidify to a stable mass as it cools. Because most soils and sludges are naturally composed of glass-forming materials such as silica, they are generally processible by ISV without modification. However, a minimum alkali content (combined Na_2O and K_2O) of 1.4 wt% is necessary to carry the electrical current in the molten soil (Buelt and Thompson, 1992).

Status and Performance of Technologies for Vitrification of In Situ Materials--

The reported typical treatment rate is 3 to 6 tons per hour (U.S. EPA, 1991, EPA 540/2-91/009). Laboratory analysis has shown that ISV will provide long-term effectiveness as well as reduction in toxicity, mobility, and volume (U.S. EPA, 1992, EPA/625/R-92/002; Buelt et al., 1987). One vendor of technologies for vitrification of in situ materials is listed in VISITT (see Appendix C).

ISV has been operated at a large scale ten times, including two demonstrations on radioactively contaminated sites at the DOE's Hanford Nuclear Reservation (Buelt et al., 1989; Luey et al., 1992). Pilot-scale tests have been conducted at Oak Ridge National Laboratory, Idaho National Engineering Laboratory, and Arnold Engineering Development Center, in addition to the Hanford site. More than 150 tests and demonstrations at various scales have been performed on a broad range of waste types in soils and sludges. The technology has been selected as a preferred remedy at 10 private, EPA Superfund, and DOD sites (Hansen and FitzPatrick, 1991). One of these sites (the Parsons/ETM site in Grand Ledge, Michigan) has been selected for a technology demonstration of ISV in the EPA SITE Program (see Appendix B) (U.S. EPA, 1991, EPA/540/5-91/008). The demonstration was completed in April 1994 in one of the eight melters. About 3,000 cu yd of soil was remediated. However, some improvements are needed with melt containment and air emission control systems. Data are being reviewed and the Applications Analysis Report will soon be available from EPA. Table 4-17 provides a summary of ISV technology selection/application at metal-contaminated Superfund sites.

TABLE 4-17. SUMMARY OF IN SITU VITRIFICATION TECHNOLOGY SELECTIONS/APPLICATIONS AT SELECTED SUPERFUND SITES WITH METAL CONTAMINATION[a]

Region	Site Name/ Location/Type	Specific Technology	Key Metal Contaminants	Associated Technology	Status[b]
5	Parsons Chemical/ Michigan/soil	In situ vitrification	Mercury (low), biocides, dioxins	Not applicable	C
8	Rocky Mountain Arsenal/Colorado/ soils	In situ vitrification	Arsenic and mercury	Not applicable	S/D

(a) For more site information and implementation status, see Appendix D.

(b) Status codes: S/D - selected in ROD, subsequently de-selected, C - completed;

Estimated Cost of Technologies for Vitrification of In Situ Materials--

There have been no full-scale applications to serve as a basis for cost estimation. As with most technologies, the actual cost depends largely on site-specific conditions and requirements. ISV costs have been estimated to range from $ 360 to $790/ton (U.S. EPA and U.S. Air Force, 1993; and U.S. EPA, 1992, EPA/625/R-92/002).

Data Needs for Technologies for Vitrification of In Situ Materials--

The data needs for ISV are discussed in Table 4-18.

TABLE 4-18. SPECIFIC DATA NEEDS FOR IN SITU VITRIFICATION TECHNOLOGIES

Factor Influencing Technology Selection[(a)]	Conditions Favoring Success of In Situ Treatment	Basis	Data Needs
Soil composition	$>30\%$ SiO_2 $>1.4\%$ Na_2O+K_2O on dry weight basis	Required to form melt and cool to stable treated waste form (technology modifications may allow treatment of soils with lower alkali content)	Soil chemistry (whole rock analysis)
Contaminant depth	>6 ft and <20 ft	Uncontaminated overburden helps retain volatile metals As a batch process, economics improve with increased thickness of contaminated volume Treatment depth demonstrated to 20 ft	Contaminant distribution
Presence of combustible liquids	<1 to 7% depending on the Btu content of the organic	Heat removal capacity of the off-gas hood and treatment system	Contaminant composition Heat of combustion of organic materials
Presence of combustible solids	<3,200 kg combustible solids per meter of depth and >30% soil	Can generate excessive off-gas volumes on combustion	Contaminant composition and distribution
Presence of groundwater	Groundwater control required if contamination is below the water table and soil hydraulic conductivity is $>10^{-4}$cm/sec	Water inflow increases energy required to vaporize water	Contaminant distribution Location of water table
Presence of in situ voids	Void volume <150 ft^3	Can generate excessive off-gas Can cause excessive subsidence	Subsurface geology
Conductive metal content	No limit demonstrated	May cause electrical short circuits in situ	Contaminant composition and distribution
Presence of sealed containers	None present	Containers can rupture during heating resulting in a large pulse of off-gas generation	Contaminant composition and distribution
Surface slope	< 5%	Melt may flow under influence of gravity	Site surface slope
Location of structures	Underground structures and utilities located >20 ft from melt zone	Items closer than 20 ft to the melt zone must be protected from heat	Contaminant composition and distribution Subsurface conditions

(a) Use hazardous substance list and site historical records to plan total waste analysis

Source: Adapted from Buelt and Thompson (1992); Geosafe Corporation (1989); and McGrail and Olson (1992).

4.3 SEPARATION/CONCENTRATION TREATMENT TECHNOLOGIES

This subsection discusses technologies to separate and/or concentrate contaminants. Three basic types of ex situ technologies are discussed: physical separation, pyrometallurgical separation, and soil washing. Two in situ technologies are discussed: soil flushing and electrokinetic extraction.

The critical issues for application of separations technology to metal-contaminated site cleanups are whether the technology can be implemented at a reasonable cost, within the required time frame, and at the desired level of treatment effectiveness.

Separation/concentration technologies may be used either as a pretreatment to reduce the volume of material to treat, or to recover metals in elemental form or as marketable compounds. Recovery for reuse has the potential to improve the long-term effectiveness of the remediation. However for recovery to be viable, there must be a market for the material. Table F-1 (Appendix F) shows a tabulation of consumption, recycling, and economic data for some metals to indicate the relative strength of the recycling market for various metals.

4.3.1 Separation/Concentration Technologies to Treat Excavated Solids

This subsection discusses the importance, processes, advantages, and disadvantages of methods for separation/concentration remedial options. Many different process implementations are available within each of the broad classes of separation technologies described in this report. Each technology implementation has specific performance characteristics, advantages, and disadvantages. Available space limits the level of detail that can be presented for these technologies. Brief descriptions of some of the less common processes and equipment items are provided in the glossary (see Appendix K).

Processes that employ physical separation techniques such as gravity separation, froth flotation, and size separation and hydroclones, followed by hydrometallurgical separation, such as acid leaching, are generally known as soil washing.

4.3.1.1 Physical Separation/Concentration Technologies

Description of Physical Separation/Concentration--

Physical separation/concentration techniques have been used commonly in the mining industry for many years. These techniques involve the physical separation of particles from each other based on:

- Particle size
- Particle density
- Surface properties of particles
- Magnetic properties (magnetic separation)

The most common particle separation techniques are summarized in Table 4-19.

Physical separation has long been used in ore beneficiation to extract the desired metal from a mineral ore. It usually involves a series of steps that lead to successive products containing increasing concentrations of the desired metal. Each separation technique thus results in the feed being divided into at least two streams--concentrate and tailings. If the separation were 100% efficient, the concentrate would consist purely of the desired metal and the tailings would constitute the rest of the feed material. However, this is not achievable in practice, and concentrate and tailings each contain some fraction of the other. The separation efficiency sometimes is increased by isolating a third stream called middlings, which has a metal concentration somewhere between that of the concentrate and tailings. All three streams--concentrate, middlings, and tailings--can be treated further to recover additional metal value.

TABLE 4-19. PARTICLE SEPARATION TECHNIQUES

	Technique				
	Screen Sizing	Classification by Settling Velocity	Gravity Separation	Magnetic Separation	Flotation
Basic principle	Various diameter openings allow passage of different effective particle sizes	Faster vs. slower settling, due to particle density, size, shape of particles	Differences in density, size, shape, and weight of particles	Magnetic susceptibility	Suspend fines by air agitation, add promoter/collector agents, fines collect in floating froth
Major advantage	Inexpensive	Continuous processing, long history, reliable, inexpensive	Economical, simple to implement, long history	Simple to implement	Very effective for some particle sizes
Major disadvantage	Screens can plug, fine screens are fragile, dry screening produces dust	Difficulty with clayey, silty, and humic soils	Ineffective for fines	High capital and operating costs	Contaminant must be small fraction of total volume
General equipment	Screens, sieves, trommel (wet or dry)	Mechanical, non-mechanical hydrodynamic classifiers	Jigs, shaking tables, troughs, sluices	Magnetic separators	Flotation machines
Lab test equipment	Vacuum sieve/ screen, trommel	Elutriation columns	Jig, shaking table	Lab magnets	Agitair™ laboratory unit

Adapted from: Perry and Chilton (1984) and Wills (1985).

Recently, there has been a growing interest in applying physical separation techniques to soil remediation. Physical separation is applicable to remediation primarily in two situations. First, if the metal contamination is in the form of discrete particles in the soil, a technique can be applied to physically separate the metal from the soil. Second, if the metal contamination is molecular (adsorbed onto soil particles) and if the contamination is limited to a specific particle-size range, physical separation based on particle size can be used as a pretreatment to reduce the total amount of contaminated soil that must undergo final (chemical) treatment.

A slightly different mineral beneficiation method, termed *comminution*, often is used in the mining industry, usually as a precursor to the physical separation techniques described above. Comminution involves crushing and grinding the mineral to reduce the particle size to a range suitable for other physical techniques. For example, gravel-sized mineral particles can be ground down to 100 μm so that froth flotation can be applied. In soil remediation, however, comminution may not have much use other than to break up soil lumps. Generally, screening is used in soil remediation to isolate the particle size amenable to treatment.

Applicability of Physical Separation Techniques--

The applicability of the physical separation techniques mentioned in Subsection 4.3.1.1 depends, to a large extent, on particle size. The size ranges suitable for the various techniques are shown in Table 4-20. As seen in this table, many of these techniques have good applicability in the intermediate size range (between 100 and 1,000 μm). In the case of froth flotation, there is an upper limit on the size range based on the size (or weight) of the particle that the air bubbles are capable of supporting. Because soil usually contains a wide range of particle sizes and the performance of physical separation techniques depends on particle size, a single technique will often not achieve sufficient separation. In that case, a combination of techniques may be able to achieve the desired separation. The particle-size ranges shown in Table 4-20 can be used to determine which separation technique(s) should be used. Additional information on the application of these separation techniques can be obtained from U.S. EPA, 1988, EPA/540/2-88/002 and *Chemical Engineers' Handbook* (Perry and Chilton, 1984).

TABLE 4-20. PARTICLE-SIZE RANGE FOR APPLICATION OF SEPARATION TECHNIQUES

Separation Process	Particle-Size Range
Screening	
Dry screen	>3,000 μm
Wet screen	>150 μm*
Hydrodynamic classifiers	
Elutriator	>50 μm
Hydrocyclone	5 - 150 μm
Mechanical classifier	5 - 100 μm
Gravity concentrators	
Jig	>150 μm
Spiral concentrator	75 - 3,000 μm
Shaking table	75 - 3,000 μm
Bartles-Mozley table	5 - 100 μm
Froth flotation	5 - 500 μm

Adapted from: Perry and Chilton (1984) and Wills (1985).

* Wet screening at less than 75 μm reported in pilot-scale soil washing study at Sand Creek Superfund Site, Commerce City, Colorado (URS, 1992).

Recently, physical separation techniques have been increasingly evaluated for or applied to remediating contaminated waste sites. Table 4-21 lists some of these applications. Use of such applications can be expected to continue to increase.

Typical Combination of Physical Separation Techniques--

A classic example of the use of physical separation techniques for soil remediation is the work being conducted by a Bureau of Mines Research Center (BMRC) for the Naval Civil Engineering Laboratory (NCEL) (Johnson, et. al., 1993 and 1994). The NCEL is researching the remediation of lead-contaminated soils associated with small arms ranges. Lead is present in the form of both particulates (bullets and bullet fragments) and molecular adsorbate. Particulate lead often is distributed across all size ranges in the soil. NCEL, in conjunction with BMRC, wanted to explore the possibility of using physical separations to remove particulate lead before using stabilization or soil washing to treat the adsorbed lead. BMRC used its knowledge of mining techniques to develop a separation scheme that, in pilot studies, recovered a significant amount of lead from soils taken from various sites. In fact, for one of the sites where lead contamination was predominantly particulate, physical separation was able to recover lead to a level where the soil passed the TCLP test without having to undergo further chemical treatment. A field demonstration was completed in August 1993 (Jeffery Heath, Naval Facilities Engineering Services Center, Port Hueneme, CA; personal communication, June 1993). Several problems were encountered during testing, which included the disposition of residual lead from the gravity circuit, smears of once molten lead trapping soil grains and attaching to larger particles, and fine lead trapped on wood surfaces (Johnson, et. al., 1993).

TABLE 4-21. EXAMPLES OF APPLICATIONS OF PHYSICAL SEPARATIONS TO WASTE SITES

Site	Application	Vendor/ technology	Separation equipment	Performance
Alaskan Battery Enterprise, SITE Demonstration Program	Soil contaminated by broken lead batteries	Brice Environmental Service Corp. (BESCORP) Soil Washing System	Wet screen, hydraulic separators, spiral classifier, clarifier	61-85% lead removal; sand fraction passed TCLP test, gravel fraction failed TCLP test SITE Applications Analysis Report, EPA/540/AR-93/503
US. Army Corps of Engineers, Confined Disposal Facility, Saginaw Bay, MI	Soils, sediments contaminated with metals, PCBs, organics, radionuclides	Bergmann USA/soil and sediment washing technology	Screen, trommel screw, heavy medium separator, elutriation	SITE Demonstration Bulletin, EPA/540/MR-92/075
Montclair/West Orange, New Jersey, Radium Site and Glen Ridge Radium Site - Demonstration	Separately, highly radioactive contaminated soil from low radioactive soil	Office of Radiation and Indoor Air/Volume Reduction/ Chemical Extraction (VORCE) technology	Mechanical classifiers, attrition mill, trommel, hydrocyclone, screen, clarifier, filter press	54% of the total soil volume had low level of contamination (below cleanup target) and waste separated from the rest of the soil
Gould, Portland, Oregon, Battery site	Soil and battery casings contaminated with lead	Canonie Environmental	Attrition scrubbing, washing, gravity separation	Site cleanup in progress
Twin Cities Army Ammunition Plant (TCAAP), New Brighton, Minnesota	Soil contaminated with metals	COGNIS/BESCORP soil washing/soil leaching process	Trommel, separation chamber, jig	Lead levels in soil were reduced to 100 ppm from as high as 86,000 ppm.

ND = no data

The final separation scheme arrived at by BMRC after trying different combinations is shown in Figure 4-1. Although many users could probably achieve acceptable results with less complex operations, this flowchart shows how each piece of equipment was optimized to do what it does best.

The lead-contaminated soil first is loaded into a feed hopper through a 1-inch grizzly. The grizzly removes rocks, branches, etc. The soil is fed via a conveyor belt to a two-deck (3 mesh and 20 mesh) vibrating screen. Water is added at the screen for wet screening; alternatively, a 20% slurry of the soil in water could be prepared separately and fed to the screen. The +3-mesh fraction containing a combination of bullets, bullet fragments, and pebbles is collected in a drum. This fraction can be sent to a lead smelter for recycling. The −3+20-mesh fraction is sent to a jig, and the jig concentrate (consisting of lead fragments) is drummed for recycling. The overflow from the jig goes to chemical treatment (heap leaching in this case).

The −20-mesh fraction from the screen goes to a spiral classifier to remove slimes. The slimes (ultra-fine particulate) go to the thickener for dewatering. The sludge from the thickener is fed to a Bartles-Mozley table. The concentrate from the table is dewatered in a spiral classifier and drummed for recycling. The tailings are dewatered, first in a thickener (with addition of flocculant), and then in a centrifuge. The solids from the centrifuge are further treated chemically.

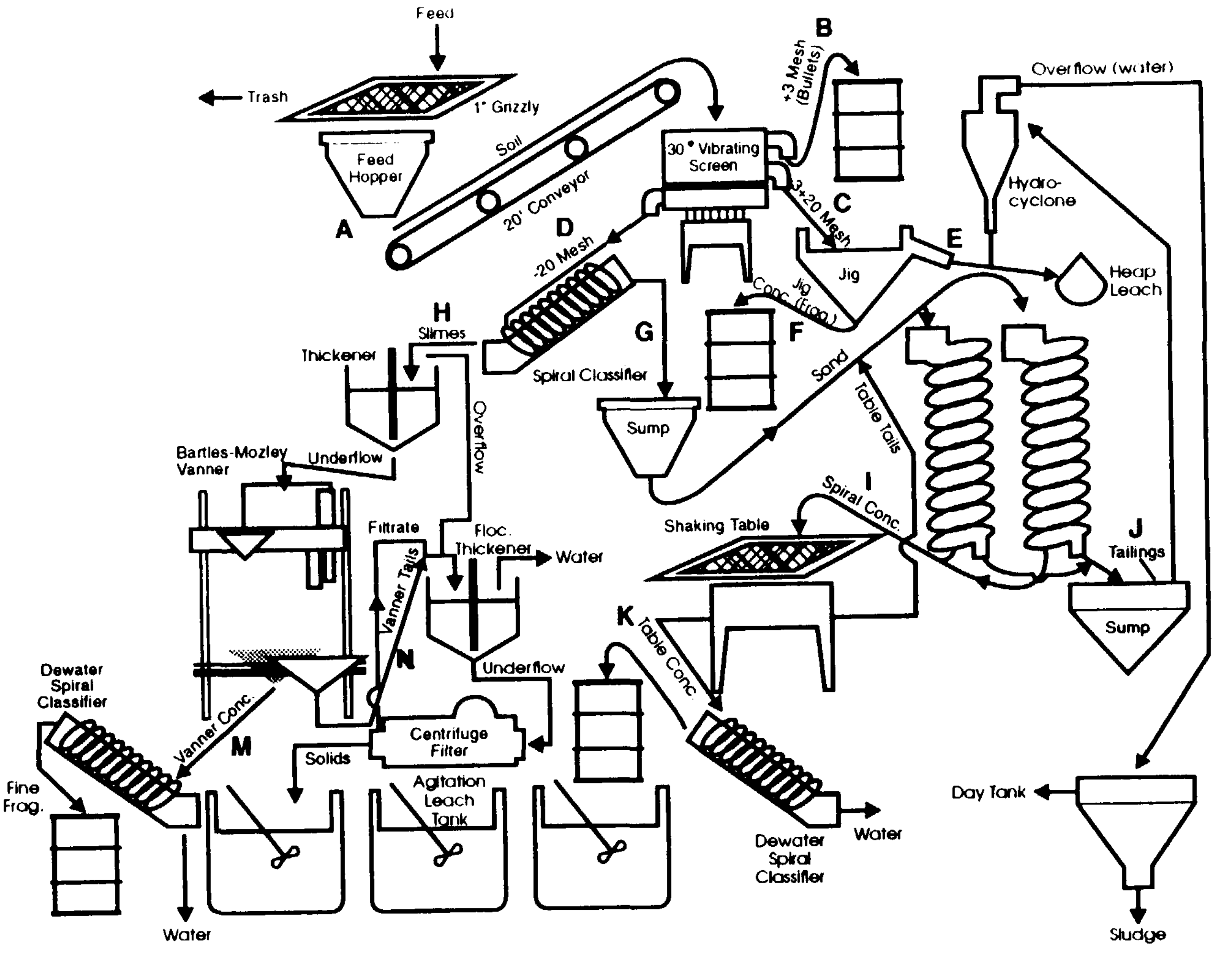
The bulk of the −20 mesh fraction coming out of the screen and through the first spiral classifier is collected in a sump, from which it is pumped to two spiral concentrators. The tailings from the spiral are dewatered in a hydrocyclone and sent to chemical treatment. The overflow water from the hydrocyclone is clarified and sent to a day tank for storage and reuse. The concentrate from the spirals is sent to a riffled shaking table. The table concentrate is dewatered in a spiral classifier and collected in a drum for recycling. The table tailings are recirculated back to the top of the spiral concentrators.

All the equipment in the flowchart is expected to fit on two or three 40-ft × 8-ft trailers. A throughput of 1.5 tons/hr of untreated soil is possible with relatively small equipment. The advantage of using physical separation to remediate lead-contaminated soils is the ability to recover large amounts of lead without the use of large volumes of extraction fluid. Very little lead is left in the soil that goes on to chemical treatment. Because the subsequent chemical treatment is heap leaching, the use of wet separation is justified and the water added to the soil forms part of the extractant (acetic acid) liquid.

Another example of the use of physical separation techniques for soil remediation is the work being conducted by MSRDI for Energy and Environmental Research Center (EERC).

The MSRDI system employs physical methods to remove elemental mercury from soil by gravity separation, and a chemical leaching procedure to extract the remaining complexed metal. For the demonstration, it was operated in a batch semi-continuous mode. With this process, the material is placed in a cement mixer and slurried to a relatively uniform consistency. The slurry is passed through a 10-mesh vibrating screen. Material smaller than 10 mesh is pumped to a two-stage Neffco concentrator. The elemental mercury and other heavy materials are retained in the concentrator and then passed through a spiral concentrator.

The fine materials are collected and a flocculating agent is added to promote gravity settling. A leachant is passed through the thickened material to remove the mercury, which is subsequently precipitated out of the leaching solution. The precipitant and the free mercury collected during the physical separation step are heated in a retort to produce elemental mercury (HazTech News, May 1994).



[a] Letters designate streams in Table 4-25.

Figure 4-1. Separation scheme for removal of lead from soil.

(Source: Jeffery Heath, Naval Facilities Engineering Services Center, Port Hueneme, CA; personal communication; June 1993).

Status and Performance of Physical Separation Techniques--

All the physical separation techniques discussed in the previous subsections are used commercially in the mining industry. Complex physical separation process combinations are just beginning to be applied to separation/concentration for metal-contaminated solids. Most equipment can be purchased off the shelf in standard sizes. However, a suitable combination based on the feed specifications must be determined and the process units must be carefully integrated to meet cleanup goals, operate efficiently, and minimize residuals.

The performance of these physical separation techniques depends on the size range and density difference of the feed material. The feed material should be characterized to find the particle size range of the soil and the contaminant distribution within each size range. Size distribution can be readily determined in a laboratory by passing a small sample of air-dried soil from the site through a series of standard sieves. Each size fraction is then subjected to a chemical (metals) analysis to determine the distribution of the contaminants among various size fractions.

If the density difference between the soil and contaminant particles is significant, classification followed by gravity concentration techniques should perform well. Actual recoveries cannot be predicted without tests on site-specific soils; however, the efficiency of separation can be estimated by the following "concentration criterion" (cc) (Wills, 1985):

$$cc = \frac{S_h - S_f}{S_l - S_f}$$

where, S_h = specific gravity of heavy particles (usually metal contamination)
S_f = specific gravity of separation fluid medium (usually water)
S_l = specific gravity of light particles (usually soil)

If cc is greater than 2.5, gravity concentration can be expected to perform well. Between 1.25 and 2.5, concentration should still be feasible; below this the separation may not be feasible. Examples of the concentration criteria for various elements and compounds are shown in Table 4-22. Good size control through the judicious use of screens and classifiers before gravity concentration will enhance the efficiency of the concentration. Furthermore, small particles reduce the processing rate and/or separation efficiency of gravity concentration and should be removed prior to gravity separation.

Other equipment-related variables can be adjusted to improve performance. For example, one of the most important variables is the water balance in the separation scheme. Most gravity concentrators have an optimum solids level for the feed slurry. Good solids level control is important, especially for the initial feed. As the material travels through the separation scheme, water can be added or removed as required with the use of washwater lines or thickeners and hydrocyclones.

In jigs, the density effect can be accentuated compared with the size effect by using a short jigging cycle (i.e., short, fast strokes). The short cycle allows smaller, denser particles to be affected more by initial acceleration (mass effect) rather than by terminal velocity (size effect). For coarser particle sizes, longer, slower strokes are better. Similarly, separation in spirals can be improved by selecting a spiral with a suitable channel slope. Spirals generally are manufactured with varying slopes of the spiral channel. Gentler slopes are provided for smaller density differences, but with a concomitant drop in capacity. Steeper slopes are for larger density differences and larger throughputs. The performance of tables is most affected by particle size. The wider the particle size range of the feed, the lower the performance. Table performance can be affected also by adjusting the stroke. A shorter stroke and higher speed improve the separation of finer particles; a longer stroke and slower speed are suitable for coarser particles.

TABLE 4-22. ILLUSTRATION OF CALCULATION OF CONCENTRATION CRITERIA FOR GRAVITY CONCENTRATION

Heavy Material Type	Heavy Material Specific Gravity[c]	Concentration Criteria for Various Combinations of Specific Gravity		
		Light Material Specific Gravity[c]		
		2.2	2.4	2.6
Arsenic element, As_4[a]	4.7	3.1	2.6	2.3
Arsenious oxide, As_2O_3	3.9	2.4	2.1	1.8
Cadmium metal, Cd	8.6	6.3	5.4	4.8
Cadmium oxide, CdO[b]	7.0	5.0	4.3	3.8
Chromium metal, Cr	7.1	5.1	4.4	3.8
Chromic oxide, Cr_2O_3	5.2	3.5	3.0	2.6
Chromite, $FeCr_2O_4$	4.5	2.9	2.5	2.2
Lead metal, Pb	11.3	8.6	7.4	6.4
Cerussite, $PbCO_3$	6.5	4.6	3.9	3.4
Lead oxide, PbO[b]	9.3	6.9	5.9	5.2
Mercury metal, Hg	13.5	10.4	8.9	7.8
Mercuric oxide, HgO	11.1	8.4	7.2	6.3

(a) Beta form.
(b) Amorphous form.
(c) Specific gravity values used for illustration. In practice, measured particle specific gravities should be used.

Particle size also is important in froth flotation, because the bubbles will not carry particles large and heavy enough to overcome the forces of adhesion at the bubble-particle interface. Another factor affecting flotation performance is pH. Generally a higher pH is more suitable to flotation, because most collectors are stable in this range. Alkalinity is maintained by the addition of lime.

If the contamination is adsorbed on matrix particles, characterization and analysis should be designed to indicate if contamination is associated predominantly with a particular size fraction. Physical separation based on size (screening or classification) would then be suitable.

The performance of the various stages in the BMRC separation scheme shown in Figure 4-1 is given in Table 4-25. Starting with 1.5 tons of raw contaminated soil, Table 4-23 shows the distribution of the feed into various fractions and the amount of lead in each fraction. The "overall operation" columns show the product weight and lead content as a percentage of the total values in the initial feed. For example, starting with 1.5 tons of lead-contaminated soil feed, 0.148 ton or 9.9% is retained in the jig concentrate.

Also, starting with 316.2 lb of lead in 1.5 tons of contaminated soil, 93.6 lb or 29.6% of the lead is retained in the jig concentrate; this is determined by analyzing a sample of the jig concentrate which showed 31.67% lead ("stream assay" column). The "unit operation" column shows the product weight and lead content as a percentage of the feed to a particular unit process. For example, 59.8% of the material delivered to the jig is retained in the tailings and 40.2% is retained in the concentrate. Also, 99.9% of the lead delivered to the jig is retained in the concentrate versus 0.1% in the tailings. The last two columns indicate the water balance maintained at various stages of the operation.

TABLE 4-23. PERFORMANCE OF SEPARATION UNIT PROCESSES FOR LEAD REMOVAL

		Overall Operation				Unit Operation			
Stream[a]	Dry Wt. (ton)	Wt. Dist. (%)	Pb Dist. (%)	Wt. Pb in Stream (lb)	Stream Assay, Pb (%)	Wt. Dist. (%)	Pb Dist. (%)	Percent Solids of Stream	Water (gpm)
Feed (A)	1.5	100	100	316.2	10.54	100	100	100	0
+3 mesh (B)[b]	0.127	8.46	59.44	187.95	74.07	8.46	59.44	70	0.22
-3+20 mesh (C)	0.368	24.53	29.64	93.72	12.73	24.53	29.64	70	0.63
-20 mesh (D)[c]	1.005	67.0	10.92	34.53	1.72	67.01	10.92	25	12.05
JIG T (E)	0.22	14.68	0.03	0.09	0.036	59.84	0.1	10	7.92
JIG C (F)	0.148	9.85	29.61	93.63	31.67	40.16	99.9	60	0.39
CLS SAN (G)	0.7	46.66	6.38	20.17	1.44	69.63	58.43	75	0.93
CLS SLI (H)	0.305	20.35	4.54	13.36	2.35	30.37	41.57	9	12.33
SPRL C (I)	0.026	1.73	3.57	11.29	9.35	3.7	55.9	65	0.06
SPRL T (J)	0.674	44.93	2.81	8.89	0.283	96.3	44.1	23	6.02
TBL C (K)	0.002	0.13	2.98	9.42	80.8	7.5	83.5	40	0.01
TBL T (L)	0.024	1.6	0.59	1.87	1.3	92.5	16.5	5	1.82
BM C (M)	0.016	1.07	1.56	4.74	13.65	5.24	33.09	15	0.36
BM T (N)	0.289	19.28	3.04	9.61	1.53	94.73	66.91	6	18.1

a T = tailings; C = concentrate; CLS = classifier; SAN = sands; SLI = slimes; SPRL = spiral; TBL = table; BM = Bartles-Mozley table. Letters following stream description indicate stream location on figure 4-1.

b + # = Retained on screen size #

c - # = Passes through screen size #

(Source: Jeffery Heath, Naval Facilities Engineering Services Center; Port Hueneme, CA; Personal Communication, June 1993.)

Note that a simple screening step (+3 mesh) results in 59.4% of the lead in the original feed being removed into a stream that contains 74.1% lead. A second screening step (-3+20 mesh) removes another 29.64% of the lead in the original feed. Thus, almost 90% of the original lead contamination is removed just by screening. Jigging concentrates the -3+20 mesh stream from the screen from 12.7% lead to 31.7% lead, making the material easier to sell to a recycler. The classifier removes the slimes in preparation for the spiral concentrator and table steps. The lead in the slimes is upgraded from 2.4% to 13.7% with the Bartles-Mozley table. The spiral concentrator upgrades the classifier sands from 1.4% lead to 9.4% lead. The shaking table upgrades the spiral concentrate from 9.4% to 80.8% lead, again a lead concentration sufficient to make recycling attractive.

Preliminary data from the tests conducted by MSRDI system for EERC indicates that physical separation alone removed 80% of the mercury from sandy soils containing 15,370 mg/kg, but less than 30% from clays that had starting levels of 920 mg/kg. Following the leaching step, the mercury levels were 10 mg/kg in the sandy soil and 33 mg/kg in the clay soils. The overall removal rate was 99.9% in the sandy soils and 96.4% in the clay soils. A total of 579.8 g of elemental mercury was recovered from the sandy soil, and 10.8 g from the clay soil (HazTech News, May 19, 1994).

Estimated Costs of Physical Separation Techniques--

Based on two SITE demonstrations conducted recently at Escambia Wood Treating site in Pensacola, Florida and Toronto Port Industrial District, the cost estimates to remediate 20,000 tons of contaminated soil are in the range of $68-$73/ton in 1993 dollars (U.S. EPA, 1993, EPA/540/AR-93/508 and U.S. EPA, 1993, EPA/540/AR-93/577). The Toronto Harbor Commissioners (THC) soil recycle treatment train consisted mostly of physical separation equipment including screen, trommel, hydroclone, Lamellar separator, and attrition scrubbers. EPA RREL's Mobile Volume Reduction Unit has a mixing chamber, trommel, and two sets of screens. (Note: Although the target compounds for these SITE Demonstrations did not include metals, the technologies are believed to be applicable to metals utilizing similar processing techniques for soils.)

Physical Separation Data Needs--

Characterization of the site soil is an important first step in determining the suitability and selection of physical separation techniques. Table 4-24 describes some of the parameters to be measured. Not all these parameters may be required at each site. In most cases, the two most important parameters are particle size and contaminant metal concentrations in each size class. The other parameters, however, may be important at specific sites. For example, at a site contaminated with lead shot, the concentration criterion may be the most important parameter to determine. Also to be noted is that, although floatability is mentioned as a characterization parameter to determine the suitability for separability by flotation, this characteristic can be altered by adding flotation reagents. Following this characterization, bench-scale tests can be performed to determine the suitability of each separation technique.

For most applications, off-the-shelf equipment can be purchased; rarely, a particular piece of equipment may have to be custom-designed. Fairly high throughputs can be obtained with relatively small separation equipment, and bench and pilot tests often can be combined. Care must be taken that the bench/pilot equipment simulates the field equipment as much as possible. For example, success in screening air-dried soil in a laboratory sieve may not be indicative of the ease of screening in the field, especially at lower mesh sizes. Or, dewatering with a laboratory vacuum filter may not be indicative of dewatering with a bowl centrifuge in the field. If bench-scale equipment is not available or is very expensive, vendors often can perform a test on a small sample of the site soil for nominal or no fee. In fact, vendors of separation equipment are a great source of information to be tapped. Representatives of vendors or manufacturers can often guide potential users in the application and effectiveness of their equipment.

TABLE 4-24. SPECIFIC DATA NEEDS FOR PHYSICAL SEPARATION TECHNOLOGIES

Factor Influencing Technology Selection[a]	Conditions Favoring Success of Physical Separation	Basis	Data Needs
Particle size	See Table 4-20	Generally, separation improves with higher particle sizes. Minimum particle size level acceptable shown in Table 4-20. High-slimes (ultrafines) level undesirable for gravity concentration.	Particle-size analysis
Contaminant metal concentration in each size class	Higher concentrations in specific size classes favorable.	Large concentrations of metal contaminants in specific size classes make size separations worthwhile.	Chemical analysis for metal concentration by size class
Concentration criteria[b]: $cc = \frac{S_h - S_f}{S_l - S_f}$	cc > 2.5 is favorable cc > 1.25 is acceptable	The larger the density difference between metal and soil, the better the separation.	Specific gravities of metal contaminant and soil
Moisture content of soil	Low moisture favorable for dry separations, high moisture favorable for wet separations	High moisture content can interfere with dry processing such as dry screening.	Moisture content of soil
Particle shape	Variable	Round particles (e.g., lead shot) can roll off shaking table; flat particles (e.g., mica) may not move on table; elongated particles could pass through screens.	Visual examination of particles
Waste complexity	Fewer types of metal preferred	Multimetals complicate separation unless all metals enrich to the same separation fraction.	Waste composition
Spatial variation in waste composition	Homogeneous waste preferred	Variations in waste composition may reduce removal efficiency.	Waste composition
Magnetic properties	Ferromagnetism	Ferromagnetic fraction can be separation from nonmagnetic fraction.	Ferromagnetic fraction
Floatability	Hydrophobic surface	Helps air bubble attach to particle surface in froth flotation.	Surface polarity

[a] Use hazardous substance list and site historical records to plan total waste analysis.

[b] S_h = specific gravity (sp. gr.) of heavy particles (element or compound), S_l = sp. gr. of light particles (soil), S_f = sp. gr. of fluid (typically water); assume S_l = 2.5 for soil if not known.

4.3.1.2 Soil Washing Technologies

Soil washing is an ex situ soil remediation technique combining aqueous extraction and contaminant separation to lower the residual contaminant concentration in treated soil to specified levels. Soil washing includes physical separation techniques (Subsection 4.3.1.1) and extraction techniques such as chemical leaching and attrition scrubbing. Physical separation is discussed in its own subsection (Subsection 4.3.1.1) because physical beneficiation is widely used as a pretreatment for many other treatment processes. Subsection 4.3.1.1 discusses operations in which the mechanisms are mainly physical and the goal is to divide the wastestream into two or more size fractions. This subsection discusses operations in which chemical mechanisms predominate and the goal is to extract a metal contaminant from the solid matrix. The technologies discussed in this subsection rely on solubility in water or chemical leaching agents to remove metals, unlike the physical separation processes that separate metal-rich and metal-depleted phases based on physical properties such as size, shape, and density.

Description of Soil Washing Technologies--

Soil washing is a water-based process for mechanically scrubbing excavated soil to remove contaminants in two ways: by dissolving or suspending them in the wash solution or by concentrating them into a smaller volume of soil through particle size separation techniques. Soil washing systems that incorporate both techniques achieve the greatest success with soils contaminated with heavy metals and organic contaminants. Contaminants tend to bind chemically and physically to clay and silt particles. The silt and clay, in turn, tend to attach physically to sand and gravel. The particle size separation aspect of soil washing first scours and separates the silts and clays from the clean sand and gravel particles. The process then scrubs the soluble contaminants from the particle surfaces and dissolves them into the liquid phase. The soil washing process uses various additives (surfactants, acids, chelating agents) to increase separation efficiencies. The washed soil, after successful testing, can be returned to the site or reclaimed. The aqueous phase and the clay/silt/sludge fraction contain high concentrations of contaminants. These two streams become waste feed for other on- or off-site separation/concentration, recovery, or disposal.

Typical Treatment Combinations With Soil Washing Technologies--

Soil washing often incorporates physical separation techniques (see Subsection 4.3.1.1). Physical separation also can reduce the volume of material needing treatment. In many soils the metal contaminant is bound to the smaller particles in a soil matrix. Physical methods will separate a clean coarse fraction from a contaminated fine fraction. Soil washing requires intimate contact of the solid contaminated matrix with an extraction fluid. The presence of large clumps or debris interferes with good contact, so pretreatment to remove or crush/grind oversize material normally is required.

Soil washing transfers the metal from the contaminated matrix into solution or converts it to a compound that subsequently can be separated from the treated matrix. Processing typically requires several volumes of washing water or leach solution per unit volume of matrix treated. The extraction fluid typically requires treatment to reduce metals to acceptable levels prior to reuse or discharge. Chemical leaching solutions are regenerated for reuse to leach the next batch of material. Reuse is required both to recover the economic value of the leaching chemicals and to avoid the environmental impact associated with treatment and discharge of waste solutions. If the goal of soil washing is to recover metal value, further processing of the leaching solution may be required to remove impurities, increase the metal concentration, or both. The full range of classical solution processing methods are available for upgrading the leach solution. The most commonly used methods are ion exchange and solvent extraction. The concentrated and purified metal-bearing solution is usually treated to reduce the metal salt or complex to metal or to convert it to a marketable compound. Reduction to metal is accomplished by electrowinning or by using a reducing gas such as hydrogen. Typical treatment combinations are shown in Table 4-25.

TABLE 4-25. TYPICAL TREATMENT TRAINS FOR SOIL WASHING TREATMENT AT METAL-CONTAMINATED SITES

Materials Handling	Pretreatment	Post-treatment/Residuals Management
Excavation	Screening for debris removal	Metal recovery from extraction fluid by aqueous processing (amalgamation, ion exchange, electrowinning, etc.)
Dredging	Size reduction for oversize material	
Conveying	Physical separation to separate rich and lean fractions	Pyrometallurgical recovery of metal from sludge
		Processing and reuse of leaching solution
		S/S treatment of leached residual
		Disposal of solid process residuals (preferably below the frostline and above the water table)
		Disposal of liquid process residuals

Applicability of Soil Washing Technologies--

Soil washing is less capital-intensive and thus usually is more efficient than pyrometallurgy if the metal concentration is low (several percent to parts per million) or the quantity to treat is small. However, economies of scale still make soil washing more cost effective for larger volumes.

Soil washing solutions can range from pure water or water supplemented with surfactants or chelating agents to concentrated acids or bases. The loaded extraction fluid is then treated for removal of contaminants. Heavily contaminated soils are commonly treated several times in a multistage countercurrent treatment system. A similar process for in situ treatment of soils is referred to as soil flushing (discussed in Subsection 4.3.2.1).

An extraction fluid typically can be selected to remove almost any metal contaminant. However, the dissolution action of the extraction fluid typically is specific to a limited range of chemical forms of a metal. Thus, most extraction solutions are effective only for a narrow range of contaminant and matrix combinations. The major challenges in selecting economically viable extraction solutions are the cost of the solution, its compatibility with the contaminated media, possible side reactions with the mixture of contaminants present, and treatment or regeneration of the extraction solution.

Chelating agents can be added to the wash solution to improve metal removal. The chelating agent reacts with the metal to form a water-soluble metal-chelate complex. Ethylenediaminetetraacetic acid (EDTA), citric acid, and diethylenetriaminepentaacetic acid (DTPA) are chelation/complexing agents considered for extracting metals (R.F. Weston, 1987, AMXTH-TE-CR-86101). Chelating agents can be expensive and difficult to recover.

Soil washing with concentrated acids or bases is an option for metal contaminants bound tightly to the solid matrix and for which less aggressive extracting solutions are not effective. The methods and equipment used are similar to those used for soil washing with milder solutions. The major requirement is to obtain good contact between the contaminated matrix and the extraction solution. Acid leaching uses the solubility of metals in acid solutions to transfer metals from the waste to a solution. The process concentrates the constituent(s) leached by the acid solutions. The contaminant-laden solution can then be filtered to remove residual solids and neutralized to precipitate solids containing high concentrations of the constituents of interest, which can be further treated in metal recovery processes. Alternatively, the acid solutions can be electrolyzed to recover relatively pure metals. An acid leaching system usually consists of a solid/ liquid contacting unit followed by a solid/liquid separator. The most frequently used acids in industrial leaching processes include sulfuric (H_2SO_4), hydrochloric (HCl), and nitric (HNO_3). Acidic solutions dissolve basic metal salts such as hydroxides, oxides, and carbonates. Although any acidic pH theoretically can be used, acid leaching processes are normally run at a pH from 1 to 4. Although less common, some metals are better leached using alkaline or carbonate leachate (U.S. EPA, 1991, *Treatment Technology Background*). Using strong acids to treat a solid waste matrix may present problems due to the potential hazards of the residues.

Status and Performance of Soil Washing Technologies--

Soil washing treatment methods are being actively developed for CERCLA wastes as evidenced by the large number of systems listed in VISITT (see soil washing and acid extraction in Appendix C). The COGNIS TerraMet® soil remediation system is being used for full-scale remediation of about 7,000 tons of lead-contaminated soil at the Twin Cities Army Ammunition Plant, New Brighton, Minnesota. The process recovers larger lead particulates by physical separation and dissolves residual lead with a proprietary solvent. The solvent is regenerated and the lead recovered (Fix and Fristad, 1993).

A process for treating soils contaminated with metals and organics was demonstrated at an industrial site within the Toronto Port Industrial District. The process involves physical separation to reduce the volume of soil requiring treatment, acid extraction, and selective chelation to dissolve metals, and biological treatment of organics. Metals are recovered from the extraction solution. A demonstration under the SITE Program was completed in the spring of 1992 (U.S. EPA, 1992, EPA/540/R-92/077). The Applications Analysis Report (U.S. EPA, 1993, EPA/540/AR-93/517) is available from EPA.

Many of the metal extraction processes are derived from processes using water-surfactant-based soil washing to remove organics from soil. Organic removal by soil washing is a more mature technology, but some soil washing systems have been tested for treatment of metal-contaminated solids. More aggressive solvent systems are under development for removal of metal contaminants. A review of innovative technology applications at Superfund sites based on RODs completed by FY 91 indicates that soil washing is the selected remedy at 20 Superfund sites. Nine of these sites are wood-treating facilities, and several others are pesticide manufacturers or battery-recycling sites. Several of the sites, as summarized in Table 4-26, include the site types and metals emphasized in this document.

Estimated Costs of Soil Washing Technologies--

As can be seen from Table 4-26, only one metal site was identified where soil washing implementation has been completed (King of Prussia, New Jersey). At another site, Twin Cities Army Ammunition Plant, Minnesota, soil washing/acid extraction is in progress.

Vendor-estimated costs for a commercial soil washing system are shown in Table 4-27. The EPA VISITT Version 3.0 contains information from 20 vendors of soil washing technology and 5 vendors of acid extraction technology. The vendors reported costs for soil washing and acid extraction ranging from $6 to $300/ton and from $220 to $390/yd^3, respectively (U.S. EPA, 1993, EPA/542/R-93-001). Although these cost estimates were not reviewed for this report, it is the author's opinion that cost estimates less than $50/ton should be regarded with extra caution.

TABLE 4-26. SUMMARY OF SOIL WASHING TECHNOLOGY APPLICATIONS AT SELECTED METAL-CONTAMINATED SUPERFUND SITES[a]

Region	Site Name/Location	Specific Technology	Key Metal Contaminants	Associated Technology	Status[b]
2	Ewan Property New Jersey	Water washing	Chromium, lead, copper, barium	Pretreatment by solvent extraction to remove organics	S
2	GE Wiring Devices Puerto Rico	Water with potassium iodide solution as an additive	Mercury	Treated residues disposed on site and covered with clean soil	S
2	King of Prussia New Jersey	Water with washing agents as an additive	Chromium, copper, silver	Sludges to be land disposed	C
5	Zanesville Well Field Ohio	Soil washing	Lead, mercury	Pretreatment with soil vapor extraction to remove organics	S
5	Twin Cities Army Ammunition Plant, New Brighton, Minnesota	Soil washing	Lead, antimony, cadmium, chromium, copper, mercury, nickel, silver	Soil leaching	I
9	Sacramento Army Depot California	Soil washing	Chromium, lead	Offsite disposal of wash liquid	S/D

(a) For more site information and implementation status, see Appendix D.

(b) *Status Codes: S - selected in ROD; I - in operation, not complete; C - completed; S/D = selected, but subsequently De-selected.*

TABLE 4-27. EXAMPLE SOIL WASHING COST DATA ($/ton)

	Volume (Short tons)			
Cost item	25,000	50,000	100,000	200,000
Depreciation[a]	40	30	15	12
Mob and demob	8	4	3	1
"Normal" site prep	12	6	4	2
Material handling	15	15	15	15
Labor	30	25	20	15
Chemicals	15	15	15	15
Maintenance	8	6	4	2
Safety equipment	3	3	3	3
Utilities	8	8	8	8
Process testing	15	12	8	5
Disposal of residuals (10% Assumption)	32	32	32	32
Management, engineering overhead, and profit	70	60	48	40
Net price ($/short ton)	$256	$216	$175	$150

(a) Major process equipment items included in the cost estimate are wet screen, hydrocyclone, clarifier, surfactant wash unit, froth flotation cell, lamella clarifier, and belt filter press.

Source: Alternative Remedial Technologies, Inc. (Tampa, FL) brochure.

Data Needs for Soil Washing Technologies--

The data needs for selection and application of soil washing technologies are shown in Table 4-28.

4.3.1.3 Pyrometallurgical Separation Technologies

This subsection describes methods using high-temperature processes to treat a metal-contaminated solid for recovery of metals as metal, metal oxide, ceramic product, or other useful form. Some companies providing pyrometallurgical metal recovery are listed in Appendix F.

Description of Pyrometallurgical Separation Technologies--

Pyrometallurgy is a broad term encompassing techniques for processing metals at elevated temperature. High-temperature processing increases the rate of reaction and often makes the reaction equilibrium more favorable, lowering the required reactor volume per unit output. It is the oldest type of metal processing dating back to the origins of extracting useful metals from ore. The earliest recorded use of pyrometallurgy was conversion of copper oxide ores to copper metal by heating with charcoal. This early example of pyrometallurgy was well established by 3,000 B.C. Pyrometallurgy offers a well-developed and powerful collection of tools for recovery of metals from waste materials.

Typical Treatment Combinations With Pyrometallurgical Separation Technologies--

Pyrometallurgical processing usually is preceded by physical separation processes to produce a uniform feed material and/or upgrade the metal content. Solids treatment in a high-temperature furnace requires efficient heat transfer between the gas and solid phases while minimizing particulate in the off-gas. The particle-size range that meets these objectives is limited. The presence of large clumps or debris slows heat transfer, so pretreatment to remove oversize material normally is required. Fine particles become en-

TABLE 4-28. SPECIFIC DATA NEEDS FOR SOIL WASHING TECHNOLOGIES

Factor Influencing Technology Selection[(a)]	Conditions Favoring Success of Treatment	Basis	Data Needs
Total metal concentration	Not specified	Determine concentration targets or interfering constituents, pretreatment needs, and extraction fluid	Waste composition
Leachable metal concentration	Not specified	Determine extractability of target constituents and post-treatment needs	Waste leachability
Particle-size distribution	>2 mm	Oversize pretreatment requirements	Particle size distribution
	0.25-2 mm	Effective soil washing	
	0.063-0.25 mm	Limited soil washing	Distribution of contaminants to various solid and liquid phases
	<0.063 mm	Clay and silt fraction–difficult soil washing (up to 20% clay may sometimes be tolerable)	
Clay content	Low is preferred	Determine sorption characteristics of the waste matrix	Soil color, texture, and composition
Type and size of debris	No debris preferred	Presence of debris increases pretreatment requirements	Waste composition
Complexity of waste mixture	Less complexity is beneficial	Complex mixture increases difficulty in formulation of a suitable extraction fluid	Contaminant composition
Waste composition variation	Homogeneous material preferred	Variation in feed composition complicates processing	Waste composition
Waste buffering capacity and pH	Low is preferred with acid extraction	High buffering capacity or pH increases acid consumption	Alkalinity
Presence of cyanides, sulfides, and fluorides	Low is preferred	Determine potential for generating fumes at low pH	Waste composition
Cation exchange capacity (CEC)	About 50 to 100 meq/kg	High CEC indicates the matrix has a high affinity for metal sorption	CEC of matrix
Humic acid content	Low is preferred	Humic content increases sorption	Soil color, texture, and composition
Extraction fluid characteristics	Fluid should have low toxicity, low cost, and allow for treatment and reuse economically	Toxicity increases both health risks and regulatory compliance costs. Expensive or nonreusable fluid increases costs.	Fluid characterization, jar testing, pilot-scale testing
Equilibrium partitioning of contaminant between matrix and extraction fluid	>1,000 mg/L metal in extractant desired	Low partitioning of contaminant into the extraction fluid increases fluid volumes required to attain cleanup goal	Equilibrium partitioning coefficient, jar testing
Contaminant solubility in water	>1,000 mg/L	Soluble compounds can be removed by water flushing	Contaminant solubility

(a) Use hazardous substance list and site historical records to plan total waste analysis. Source: Adapted from U.S. EPA 1988, EPA/540/2-88/004; U.S. EPA 1990, EPA/600/2-90/011; U.S. EPA 1992, EPA/600/K-92/003; U.S. EPA, 1990, EPA/540/2-90/017; U.S. EPA, 1992, EPA/540/S-92/011; U.S. EPA, EPA-823-B93-001; and U.S. EPA, 1991, Treatment Technology Background.

trained in the gas flow, increasing the volume of dust to be removed from the flue gas, so fine particles also are undesirable. The feed material often is pelletized to give a uniform size and improve gas flow in the reactor. In many cases a reducing agent and flux may be mixed in prior to pelletization to ensure good contact between the treatment agents and the contaminated material.

Physical separation also may be used to reduce the volume of material requiring treatment (see Subsection 4.3.1.1). In many soils the metal contaminant is bound to the smaller particles in a soil matrix. In many cases, physical methods can be used to separate a clean coarse fraction from a contaminated fine fraction. Typical treatment combinations are shown in Table 4-29.

TABLE 4-29. TYPICAL TREATMENT TRAINS FOR PYROMETALLURGICAL TREATMENT AT METAL-CONTAMINATED SITES

Materials Handling	Pretreatment	Post-treatment/Residuals Management
Excavation	Screening for debris removal	S/S treatment of slag or fly ash
Dredging	Size reduction for oversize material	Disposal of treated solid residuals (preferably below the frostline and above the water table)
Conveying	Addition of reducing agent	
	Pelletizing	Reuse of slag as construction aggregate
	Dewatering for wet sludge	Reuse of metal or metal compound
	Drying	Further processing to purify metal or metal compound
	Physical separation to separate rich and lean fractions	

Applicability of Pyrometallurgical Technologies--

Pyrometallurgical processes for waste treatment typically consist of:

- Primary treatment to convert compounds in the waste matrix to metal or matte and transfer undesirable components to a separate slag phase
- Subsequent treatment to upgrade a metal or matte

A variety of equipment types such as rotary kilns, rotary hearth furnaces, or arc furnaces may be used for pyrometallurgical processing. Pyrometallurgical separations may be used singly, in sequence, or in combination with physical, hydrometallurgical, biological, or electrometallurgical processing depending on the types of materials processed.

Pyrometallurgical separations typically require a reducing agent, fluxing agents to facilitate melting and slag off impurities, and a heat source. Although the fluid mass often is called a melt, the operating temperature, although quite high, is often still below the melting points of the refractory compounds being processed. The fluid forms as a lower melting point material due to the presence of a fluxing agent such as calcium. Volatile metals such as arsenic, cadmium, or lead enter the off-gas stream where they are oxidized and recovered by filtration or scrubbing. Nonvolatile metals such as nickel or chromium remain in the furnace and are purified by slagging.

Pyrometallurgical processing in conventional rotary kilns, rotary furnaces, or arc furnaces is most likely to be applicable to large volumes of material containing metal concentrations (particularly zinc, lead, cadmium, nickel, or chromium) higher than 5 to 20%. Lower metal concentrations can be acceptable if the metal is particularly easy to reduce and vaporize (e.g., mercury) or is particularly valuable (e.g., gold or platinum).

Pyrometallurgical separation processing for all metals except mercury is currently carried out in fixed-location facilities (see Appendix F). The flame reactor process has the potential to allow lower capital costs. Pyrometallurgical processing of smaller volumes in on-site facilities may be feasible with the newer technologies. However, economies of scale still apply. For mercury recovery, both fixed-facility and mobile thermal desorption units are available.

Status and Performance of Pyrometallurgical Technologies--

Due to the large volume of electric arc furnace (EAF) emission control waste (K061), extensive processing capability has developed to recover cadmium, lead, and zinc from solid waste matrices. Permitting is being expanded to cover other hazardous waste types. The currently available process technologies for K061 and similar materials include:

- Waelz kiln process
- Waelz kiln and calcination process
- Flame reactor process

Plasma arc furnaces currently are successfully treating K061 (EAF waste) at two steel plants. These are site-dedicated units that do not accept outside material for processing. The companies shown in Table 4-30 are reported to have the capability for processing EAF dust or similar materials to recover cadmium, lead, and zinc.

TABLE 4-30. CURRENT UNITED STATES PROCESSING CAPABILITY FOR EAF DUST AND SIMILAR MATERIALS

Company(c)	Location	Approximate design capacity (metric ton EAF/yr)	Approximate 1992 production (metric ton contained Zn/yr)	Process
Horsehead Resource	Beaumont, TX	27,000	0	Flame Reactor(a)
Horsehead Resource	Calumet City, IL	72,000	(b)	Waelz Kiln
Horsehead Resource	Monaca, PA	18,000	No Data	Flame Reactor
Horsehead Resource	Palmerton, PA	245,000	(b)	Waelz Kiln Waelz Kiln and Calcining
Horsehead Resource	Rockwood, TN	90,000	(b)	Waelz Kiln
Zia Technology, TX	Caldwell, TX	27,000	Low	Inclined Rotary Kiln

(a) Under construction.
(b) 62,000 MT/yr contained zinc for three facilities.
(c) Site-dedicated plasma furnaces not included.

The flame reactor technology was accepted into the SITE Demonstration Program in summer 1990. The prototype flame reactor system used for the SITE Program operates with a capacity of 1 to 3 tons/hour in a stationary mode at the developer's facility in Monaca, Pennsylvania. The SITE Demonstration test was conducted from March 18 to 23, 1991, on secondary lead smelter-soda slag from the National Smelting and Refining (NSR) Company Superfund site in Atlanta, Georgia. Approximately 72 wet tons of NSR waste material were processed during the demonstration. Partial test results are shown in Table 4-31. All effluent slag passed the TCLP-limits criteria. The Technology Evaluation Report (U.S. EPA, 1992, EPA/540/5-91/005) and the Applications Analysis Report (U.S. EPA, 1992, EPA/540/A5-91/005) are available from EPA.

In addition to the processes for metal recovery from EAF dust, pyrometallurgical processing capacity is available for a variety of other metal-bearing wastes. The greatest capacity and process variety for recovery of metals from solid wastes other than EAF dust is for lead recovery. Mercury, due to its relatively low boiling point and stability as a metal, is another common target for recovery. Other metals commonly recovered by pyrometallurgical methods include copper, nickel, and tin. Pyrometallurgical processes also are available for some other specialty wastes.

TABLE 4-31. METAL CONCENTRATION RANGES IN INFLUENT AND EFFLUENT FOR FLAME REACTOR PROCESS

Metal	Waste feed (mg/kg)	Effluent slag (mg/kg)[a]	Product oxide (mg/kg)
Arsenic	428 - 1,040	92.1 - 1,340	1,010 - 1,170
Cadmium	356 - 512	<2.3 - 13.5	1,080 - 1,380
Copper	1,460 - 2,590	2,730 - 3,890	1,380 - 1,780
Iron	95,600 - 130,000	167,000 - 228,000	29,100 - 35,600
Lead	48,200 - 61,700	1,560 - 11,400	159,000 - 184,000
Zinc	3,210 - 6,810	711 - 1,680	10,000 - 16,200

(a) All effluent slag passed TCLP-limits criteria.

Source: U.S. EPA, 1992, EPA/540/R-92/077.

Catalytic Extraction Processing. Molten Metal Technology has patented a catalytic extraction process (CEP) that uses a high-temperature molten metal bath to process wastes contaminated with organics and metals. The CEP dissolves the waste material into a molten metal bath operating near 3,000°F. The high temperatures and catalytic action of the metal bath convert materials to elemental form. Organic contaminants are reportedly converted to CO_2 and methane, and exit as an off-gas stream for purification and reuse. Metal impurities in the waste collect in the molten metal bath (Smith, 1991).

Secondary Lead Smelting. Secondary lead smelting is a proven technology for reclaiming lead from materials that contain 40% lead or more. Commercial secondary lead smelters typically use reverberatory and blast furnaces to heat a contaminated matrix to remove lead by a combination of melting and reduction.

The Center for Hazardous Materials Research and Exide/General Battery Corporation are demonstrating the use of secondary lead smelting to reclaim usable lead from waste materials containing between 1 and 50% lead. Waste containing 1 to 25% lead is treated in a reverberatory furnace to produce slag containing about 70% lead. The slag and other high-lead-content materials are fed to a blast furnace to produce lead metal products. SITE Program testing has been performed on a variety of waste materials including battery cases, slags, lead dross, and lead paint chips. Materials from Superfund or other contaminated sites could be mixed with other higher grade lead material for smelting (U.S. EPA, 1992, EPA/540/R-92/077). The reported treatment cost ranges from $150/ton to $250/ton for Superfund materials (Timm and Elliott, 1993). The process has been used to treat about 2.7 million pounds of lead-bearing materials from the NL Industries Superfund site (U.S. EPA, 1993, EPA/542/N-93/005).

Submerged Arc Smelting Furnace. INMETCO (Ellwood City, PA) operates a submerged arc smelting furnace to recover nickel, iron, and chromium. Solid wastes are pelletized and fed to the Rotary Hearth Furnace to reduce metal salts to the metallic form. A submerged arc furnace then processes the pretreated waste. The chromium, iron, and nickel are cast into ingots that are suitable as feed for stainless steel making. The slag is reported to be nonhazardous and suitable for application as an aggregate. Cadmium, lead, and zinc are collected as flue dust from the submerged arc furnace. The flue dust is sent to another site for metal recovery (Electrical World, 1991).

The types of waste material processed by the facility include nickel- and chromium-containing sludges, dusts, grindings, and catalysts; nickel-cadmium and iron-nickel batteries; chromium-magnesite refractories, dolomitic refractories, carbon brick and coke fines, waste magnesium powders and machinings; baghouse bags; and bags and filters for plating operations (Hanewald et al., 1992). The facility is reported to hold a permit to process RCRA waste codes D001, D002, D003, D006, D007, D008, F006, K061, and K062. The typical material quality required for the process is shown in Table 4-32.

TABLE 4-32. TYPICAL INPUT MATERIAL REQUIREMENTS FOR THE INMETCO PROCESS

Metal	Approximate Solid Waste Specification (wt% on a dry basis)
Nickel	>1.3
Chromium	>5.0
Phosphorus[(a)]	<0.05
Iron	No limit
Calcium Oxide	No limit
Magnesium Oxide	No limit
Sodium, Chloride, Potassium	<20.0
Copper	<2.0
Tin[(a)]	<0.03
Cadmium	<20.0
Sulfur	<5.0
Lead	<10.0
Zinc	<20.0
Alumina	<15.0
Silica	<15.0
Cobalt	<2.0
Molybdenum	<10.0

(a) Critical limits.

Source: INMETCO Brochure.

Mercury Recovery. Relatively few metal oxides convert easily to the metallic state in the presence of oxygen. As a result, reduction reactions typically require the presence of a reducing agent such as carbon at elevated temperatures. Mercury is one of the few exceptions. Many mercury compounds convert to metal at atmospheric pressure and 300°C or lower temperature. With a boiling point of 357°C (Chase et al., 1985), mercury is substantially more volatile than most metals. Thus, mercury and its compounds can be separated by roasting and retorting more easily than most metals, making it an ideal candidate for recycling from a wide variety of waste materials. Two vendors of thermal desorption processes for mercury recovery are listed in the VISITT database (see Appendix C).

An input concentration of 5% mercury is preferred. Typical feed includes metal and glass materials. Most plastics can be processed, but polyvinyl chloride and other halogen-containing materials must be minimized due to the potential for generation of corrosive or volatile materials during heating in the retort. Volatile or reactive metals such as lithium, arsenic, and thallium also are not allowed in the process. Quartz containers can be processed but must be crushed. Dirt, soils, and sludge-like materials can be processed if the water content is below about 40%. If the mercury is in solution, the mercury must be collected as a solid by precipitation or by adsorption onto activated carbon. As with the sludge feed, the collected solid usually contains less than about 40% water (Lawrence, 1992).

A portable thermal treatment (PTT) process for removing elemental mercury, mercury compounds, and amalgams from soil is being commercialized by Mercury Recovery Services, New Brighton, PA. The first full-scale system, which is designed to handle 12-18 tons/day, is scheduled to begin remediating a gas line site in 1994. The PTT system is one of three technologies evaluated for use on mercury-contaminated soil by the University of North Dakota's Energy and Environmental Research Center with funding from the Gas Research Institute. The other two are a physical separation/chemical leaching process developed by Mountain States R&D International, Inc., Vail, AZ, and a chemical process from COGNIS, Inc., Santa Rosa, CA.

Preliminary results from tests with the PTT process found that total mercury in sandy soils could be reduced from 12,720 mg/kg to 0.07 mg/kg. TCLP testing of the untreated soil found 0.346 mg/L of mercury in the leachate, compared to 0.0005 mg/L in the leachate following treatment in the PTT unit. In clay soils, total mercury levels of 1,090 mg/kg were lowered to 0.12 mg/kg; while the TCLP values declined from 0.065 mg/L to 0.0008 mg/L.

Estimated Costs of Pyrometallurgical Technologies--

The HRD Flame Reactor at Monaca, Pennsylvania, participated in a SITE Demonstration test. The results of the test program were the basis for developing cost estimates for several possible commercial applications of Flame Reactor technology to site remediation. The cost analyses are summarized in Table 4-33. The cost estimates are in the range of $458 to $208/ton of waste treated in 1991 dollars.

Pyrometallurgical Technology Data Needs--

The data needs for selection and application of pyrometallurgical technologies are shown in Table 4-34.

4.3.2 Description of In Situ Technologies

This section addresses two in situ technologies (soil flushing and electrokinetic) potentially applicable to the treatment of metal-contaminated soils.

4.3.2.1 Soil Flushing Technology

Soil flushing uses extraction through injection of aqueous solutions to remove contaminants from the subsurface without excavation of the contaminated materials. The leaching solution must be selected to remove the contaminant while not harming the in situ environment. Use of the leaching solution must be consistent with LDRs and other regulatory requirements.

Description of Soil Flushing--

Soil flushing is the extraction of contaminants from the soil with an appropriate washing solution to remove organic or inorganic contaminants from the soil. Water or an aqueous solution is injected into or sprayed onto the area of contamination, and the contaminated elutriate is collected and pumped to the surface for removal, recirculation, or onsite treatment and reinjection.

The contaminants are mobilized by solubilization, formation of emulsions, or a chemical reaction with the flushing solutions. After passing through the contamination zone, the contaminant-bearing fluid is collected by strategically placed wells or trenches and brought to the surface for disposal, recirculation, or onsite treatment and reinjection. During elutriation, the flushing solution mobilizes the sorbed contaminants by dissolution or emulsification.

Typical Treatment Combinations With Soil Flushing--

Soil flushing uses water, a solution of chemicals in water, or an organic extractant to recover contaminants from the in situ material. One key to efficient operation of a soil flushing system is the ability to reuse the flushing solution. A variety of water treatment techniques can be applied to remove the recovered metals and render the extraction fluid suitable for reuse. Subsurface containment barriers should be considered in conjunction with soil flushing technology to help control the flow of flushing fluids. Typical treatment combinations are shown in Table 4-35.

TABLE 4-33. ESTIMATED COSTS ASSOCIATED WITH THE HORSEHEAD RESOURCE DEVELOPMENT FLAME REACTOR SYSTEM (IN 1991 DOLLARS)

	SITE Test[a]	Commercial Operations (Scenarios 2-6)[b]				
Scenario Number	1	2	3	4	5	6
Plant Location	Monaca, PA	Monaca, PA	On-site	Monaca, PA	On-site	On-site
Capital ($ million)	2.5	2.5	3.1	4.5	6.0	10.4
Annual capacity (tons)	6,700	6,700	6,700	13,400	20,000	50,000
Cost categories	Estimated cost per ton of waste treated (1991 $)					
Site and waste preparation	c	c	c	c	c	c
Excavation of waste	93	10	10	10	10	10
Transportation of waste	129	60	6	60	6	6
Pretreatment of waste	246	21	21	20	19	17
Permitting and regulatory requirements	10	10	10	10	10	10
Capital equipment	64	64	79	58	52	36
Startup	1	1	1	1	1	1
Labor	114	78	93	39	31	18
Consumables	d	d	d	d	d	d
Oxygen	131	93	93	60	49	41
Natural gas	81	58	58	34	26	21
Utilities	11	11	11	11	11	11
Effluent monitoring[e]	0	0	0	0	0	0
Shipping, handling, and transporting residuals	f	f	f	f	f	f
Effluent slag	15	15	15	15	15	15
Oxide product[g]	–	–	–	–	–	–
Analytical test	3	3	4	2	2	1
Equipment repair and replacement	34	34	37	30	24	15
Site demobilization	0	0	10	0	7	6
Total Cost Per Ton of Waste	932	458	448	350	263	208

a SITE Demonstration test on secondary lead smelter-soda slag (see Subsection 4.3.1.2).
b Commercial operations assume metal content (lead and cadmium) 7.5% and moisture content 15% to 25%.
c Reported separately as excavation of waste, transportation of waste, and pretreatment of waste.
d Consumables costs consist of oxygen and natural gas.
e Costs for effluent monitoring are included in capital and labor cost categories.
f Costs for shipping, handling, and transporting residuals reported separately for slag and product.
g The credits or costs for disposal of oxide product are variable depending on market conditions and are not included.

Source: U.S. EPA, 1992, EPA/540/A5-91/005.

TABLE 4-34. SPECIFIC DATA NEEDS FOR PYROMETALLURGICAL TECHNOLOGIES

Factor Influencing Technology Selection[a]	Conditions Favoring Success of Treatment	Basis	Data Needs
Waste volume	Large quantity of material	Pyrometallurgical processing typically operates best with continuous feed	Risk-based waste delineation
Particle size	Not specified	Specific particle-size requirements depend on the process	Waste material particle-size distribution
Moisture content	No free moisture	Presence of water increases energy requirements High moisture increases material-handling problems	Waste moisture content
Metal content	Concentration of metals levels to be recovered should typically be in the percent range	Percentage concentrations are required to make process feasible Lower concentrations are typically processed by hydrometallurgical methods	Waste composition
Heating value of waste	Not specified	Combustibles in waste may provide some heating	Waste composition
Thermal conductivity of waste	Higher is preferred	Treatment requires the ability to transfer heat into the waste matrix	Thermal conductivity
Types of metals present	Not specified	Mixtures of volatile and nonvolatile metals require multiple processing steps	Waste composition Metals boiling point
Nitrates, sulfur compounds, phosphates, and halides	Not specified	May form corrosive acid gases Sulfur forms nonvolatile sulfides Halides can form volatile metal species	Waste composition
Alkaline metals	Not specified	Metals such as sodium and potassium decrease the slag formation temperature and increase the corrosiveness of the slag	Waste composition
Ash content of waste	Not specified	Helps quantify expected slag volume	Weight loss on ignition

(a) Use hazardous substance list and site historical records to plan total waste analysis.

TABLE 4-35. TYPICAL TREATMENT TRAINS FOR SOIL FLUSHING AND ELECTROKINETIC TREATMENT AT METAL-CONTAMINATED SITES

Pretreatment/Materials Handling	Separation/Concentration Technology	Post-treatment/Residuals Management
Flushing fluid delivery system	Soil flushing and electrokinetic	Flushing liquid/groundwater treatment and disposal
Groundwater extraction system		Air pollution control
Containment barriers		In situ soil treatment containment barriers

Applicability of Soil Flushing--

The four major elements in application of in situ flushing are (Palmer and Wittbrodt, 1991):

- Delivery of the extraction fluid to the required subsurface volume
- Interaction between the extraction fluid and the contaminant
- Recovery of the contaminant and extraction fluid from the subsurface
- Treatment of the recovered contaminant and fluid

Soil flushing requires a flushing solution that is available in sufficient quantity at a reasonable cost. Flushing solutions may include water, acidic aqueous solutions (such as sulfuric, hydrochloric, nitric, phosphoric, or carbonic acids), basic solutions (such as sodium hydroxide), chelating or complexing agents, reducing agents, and surfactants. Water will extract water-soluble or water-mobile constituents. Inorganics that can be flushed from soil with water are soluble salts such as the carbonates of nickel, zinc, and copper. Adjusting the pH with dilute solutions of acids or bases can control inorganic mobility and removal. Acidic solutions can be used to remove cationic metals or basic organic materials. Basic solutions may be used for some metals and some phenols. Chelating, complexing, and reducing agents may be needed for recovery of some metals. Surfactants can assist in emulsification of hydrophobic organics (U.S. EPA, 1991, EPA/540/2-91/021).

The technology may be easy or difficult to apply, depending on the ability to wet the soil with the flushing solution and to install collection wells or subsurface drains to recover all the applied liquids. Provisions also must be made for ultimate disposal of the elutriate. The achievable level of treatment varies and depends on the contact of the flushing solution with contaminants, the appropriateness of the solution for contaminants, and the hydraulic conductivity of the soil. The extended treatment times needed to remediate metal sites by pump-and-treat methods make it worthwhile to consider addition of soil flushing chemicals to speed or enhance contaminant removal.

Status and Performance of Soil Flushing--

Soil flushing to remove organic materials has been demonstrated at both bench- and pilot-scale. Studies have been conducted to determine the appropriate solvents for mobilizing various classes and types of chemical constituents. Several systems are in operation and many systems are being designed for remediation of Superfund sites. Most of the applications involve remediation of VOCs (U.S. EPA, 1992, EPA/542/R-92/011).

Soil flushing for inorganic treatment is less well developed than soil flushing for organics, but some applications at Superfund sites have been reported. One system is operational at a landfill with mixed organics and metals, and another is operational at a chromium-contaminated site (U.S. EPA, 1992, EPA/542/R-92/011). Several other inorganic treatment systems are in the design or predesign phases at Superfund sites. Some Superfund metal-contaminated sites that have selected soil flushing as a remedy are summarized in Table 4-36.

Estimated Costs of Soil Flushing--

Estimated costs for application of soil flushing range from \$75 to \$200/yd^3 depending on the waste quantity. These are rough estimates and are not based on field studies (U.S. EPA and U.S. Air Force, 1993). The Superfund site at Palmetto Wood, South Carolina cited costs of \$3,710,000 (capital) and \$300,000 (annual operation and maintenance). These totals, on a unit basis, equal \$185/yd^3 for capital costs and \$15/yd^3/yr for operation and maintenance (U.S. EPA, 1990, EPA/600/2-90/011).

TABLE 4-36. SUMMARY OF SOIL FLUSHING TECHNOLOGY SELECTIONS/APPLICATIONS AT SELECTED SUPERFUND SITES WITH METAL CONTAMINATION[a]

Region	Site Name/ Location	Specific Technology	Key Metal Contaminants	Associated Technology	Status[b]
2	Lipari Landfill, New Jersey	Soil flushing of a volume of soil and wastes contained by a slurry wall	Chromium, lead, nickel, mercury	Slurry wall	I
3	U.S. Titanium, Virginia	Dissolution of wastes	Ferrous sulfate	Not stated	S
10	United Chrome Products, Oregon	Soil flushing with water	Chromium	Pilot test of electrokinetic removal conducted at site Considering in situ reduction process	I

(a) For more site information and implementation status, see Appendix D.

(b) Status codes: S - selected in ROD; I - in operation, not complete, C - completed.

Data Needs for Soil Flushing--

The data needs for selection and application of soil flushing options are shown in Table 4-37.

4.3.2.2 Electrokinetic Treatment Technology

Electrokinetic technology removes metals and other contaminants from soil and groundwater by applying an electric field in the subsurface.

Description of Electrokinetic Treatment Technology--

Electrokinetic treatment uses a charged electric field to induce movement of ions, particulates, and water through the soil (Hinchee et al., 1989). The electrokinetic phenomenon occurs when liquid migrates through a charged porous medium, typically clay, sand, or other mineral particulate that normally has a negative surface charge.

The electrical field is applied through anodes and cathodes placed in the soil. Most metals form positively charged ions that migrate toward the negatively charged electrode. Metal anions such as chromates migrate to the positively charged electrode, and concentration gradients in the soil solution are established between the cathode and anode. The imposed electrical field drives diffusion of metal ions from areas of low concentration to areas of high concentration. The viscous drag due to movement of the cations also induces a net flow of water to the cathode (Marks et al., 1992).

The spacing of wells containing the cathode and anode depends on site-specific factors. The cathode and the anode housings can be provided with separate circulation systems filled with different chemical solutions to maximize recovery of metals. The contaminants are captured in these solutions and brought to the surface for treatment in a purification system.

TABLE 4-37. SPECIFIC DATA NEEDS FOR SOIL FLUSHING TECHNOLOGIES

Factor Influencing Technology Selection[a]	Conditions Favoring Success of In Situ Treatment	Basis	Data Needs
Detailed understanding of contaminant distribution and subsurface geology	Not specified	Affects the ability to deliver and recover flushing solution effectively	Distribution of the contaminant in relation to subsurface features
Hydraulic conductivity	$>10^{-3}$ cm/sec; low clay content	Good conductivity allows efficient delivery of flushing fluids	Hydrogeologic flow regime; Soil type
Equilibrium partitioning of contaminant between soil and extraction fluid	Not specified	Low partitioning of contaminant into the extraction fluid increases fluid volume required to attain cleanup goals	Equilibrium partitioning coefficient Bench- and pilot-scale testing
pH	No action levels specified	May affect treatment additives required, compatibility with materials of construction, or flushing fluid formulation	Soil pH
Buffering capacity	No action levels specified	Indicates matrix resistance to pH change	Soil buffering capacity
Contaminant solubility in water	$>1{,}000$ mg/L	Soluble compounds can be removed by water flushing	Contaminant solubility
Complex waste mixture	Less complexity is beneficial	Complex mixture increases difficulty in formulation of a suitable extraction fluid	Contaminant composition
Spatial variation in waste composition	Less variation is beneficial	Changes in waste composition may require reformulation of extraction fluid	Statistical sampling of contaminated volume
Total metal concentration	Not specified	Determine concentration targets or interfering constituents, pretreatment needs, and extraction fluid	Waste composition
Leachable metal concentration	Not specified	Determine extractability of target constituents and post-treatment needs	Waste leachability
Flushing fluid characteristics	Fluid should have low toxicity, low cost, and allow for treatment and reuse	Toxicity increases health risks and increases regulatory compliance costs Expensive or nonreusable fluid increases costs	Fluid characterization Bench- and pilot-scale testing
	Fluid should not plug or have other adverse effects on the soil	If the fluid adheres to the soil or causes precipitate formation, permeability may drop, making continued treatment difficult	Fluid viscosity
	Fluid viscosity should be low	Lower viscosity fluids flow through the soil more easily	
Presence of cyanides, sulfides, and fluorides	Low is preferred	Determine potential for generating fumes at low pH	Waste composition
Specific surface area of matrix	<0.1 m^2/g	High surface area increases sorption on soil	Specific surface area of matrix
Cation exchange capacity (CEC)	< about 50 to 100 meq/kg	High CEC indicates the matrix has a high affinity for metal sorption	CEC of matrix
Humic acid content	Low is preferred	Humic content increases sorption	Soil color, texture, and composition

(a) Use hazardous substance list and site historical records to plan total waste analysis

Source: Adapted from U.S. EPA, 1988, EPA/540/2-88/004; U.S. EPA, 1990, EPA/600/2-90/011; U.S. EPA, 1993, EPA/540/S-94/500

Typical Treatment Combinations With Electrokinetic Treatment Technology--

Electrokinetic treatment concentrates metals at the cathode to allow recovery of contaminants from the in situ material. Typically the solution will require subsequent treatment for metals removal prior to reinjection or discharge. A variety of water treatment techniques can be applied to remove the recovered metals and render the extraction fluid suitable for reuse. Water treatment methods are referenced in Subsection 4.5. Typical treatment combinations were shown in Table 4-35 (see page 4-52).

Applicability of Electrokinetic Treatment Technology--

Electrokinetic separation may be applied to enhance phase separation, concentrate ionic species, or both. Chemical species that form ions in solution that can migrate under the influence of the electrical field can be effectively concentrated. Mobility of fluids also is enhanced by the electroosmosis so the electrokinetic method can be applied to improve dewatering of a material.

Electrokinetic treatment is most applicable to saturated soil with nearly static groundwater flow and moderate to low permeability. A low groundwater flow rate is required so that ionic diffusion rather than advective flow is the main transport mechanism. Water is required to provide a polar medium for ion flow. Electrokinetic treatment is less dependent on high soil permeability than are the in situ metals extraction technologies such as soil flushing. The electrokinetic separation occurs due to ionic migration rather than bulk fluid flow. Fine-grained clay soils are reported to be an ideal medium for electrokinetic treatment (U.S. EPA, 1992, EPA/540/R-92/077). As a result, electrokinetic separation can be applied in soils where soil flushing flow rates are too low for soil flushing to be practical.

Electrochemical reactions at the electrodes are unavoidable side effects of electrokinetic separation techniques. The most likely reaction is electrolysis of the water. The reaction at the cathode is production of hydrogen gas and hydroxide ions. The hydrogen gas escapes, causing the pH to rise. Increases of pH to above 13 have been reported in the vicinity of the cathode (U.S. EPA, 1990, EPA/540/2-90/002). Similarly, evolution of oxygen and production of hydrogen ions occurs at the anode causing acidification of the anode area. During operation of electrokinetic treatment, the acid front migrates away from the anode and can contribute to dissolution and mobilization of metal contaminants (Probstein and Hicks, 1993).

Other electrochemical reactions also may occur. Chloride ions, which are often present in natural waters, may be reduced to form chlorine gas. Chemical and electrochemical processes may result in precipitation of solid materials, such as iron or chromium hydroxides, that plug pores in the formation and reduce permeability to unacceptable levels (U.S. EPA, 1991, EPA/540/2-91/009).

Status and Performance of Electrokinetic Treatment Technology--

Commercial application of electrokinetic treatment has been pioneered in Europe by Geokinetics of Rotterdam, The Netherlands, and is ongoing in the U.S. (Acar and Alshawabkeh, 1993). Field testing is reported to indicate that soil type is an important parameter in successful application of electrokinetics. Geokinetics has reported 90% contaminant removal from clayey soils but only 65% from porous soils (Steimle, 1992).

There are two major laboratory programs studying electrokinetic treatment processes. Research at the University of Colorado is currently funded by the Electric Power Research Institute. The experimental results indicate a 450% concentration factor for metal contaminants in water adjacent to the electrodes. Researchers at the Massachusetts Institute of Technology are studying electrode emplacement geometries and electrical field strengths under a grant for the Northeast Hazardous Substance Research Center (Steimle, 1992).

A field test of electrokinetic treatment was conducted at the United Chrome Products Superfund Site in Corvallis, Oregon. Groundwater chromium concentrations at the site ranged from 651 mg/L to 1 mg/L. A series of experiments compared chromium removal by water flushing alone to (1) electrokinetic migration and (2) electrokinetic migration in combination with water flow. The testing indicated that electric potential can induce migration of chromium. The process of ion migration was, however, found to be slow and could be enhanced or suppressed depending on the direction of water flow (Banerjee, 1992).

Electroacoustic soil decontamination was evaluated as an emerging technology under the SITE Program. Bench-scale testing indicated the feasibility of removing inorganic species such as zinc and cadmium from clay soils. A report describing the test results has been published (U.S. EPA, 1990, EPA/540/5-90/004).

The Electrokinetics, Inc. electrokinetic remediation system has been accepted for demonstration under the SITE Program. Bench-scale tests of soil treatment to remove arsenic, benzene, cadmium, chromium, copper, ethylbenzene, lead, nickel, phenol, trichloroethylene, toluene, xylene, uranium, and zinc were completed under various programs including the SITE Emerging Technology Program. Pilot testing and field testing are ongoing (Acar, 1992; U.S. EPA, 1992, EPA/540/R-92/077).

Estimated Costs of Electrokinetic Treatment Technology--

Electrokinetic treatment is still in the early development stage. This study found no reliable basis for estimating costs for using electrokinetic technology to treat metal-contaminated solid materials.

Data Needs for Electrokinetic Treatment Technology--

The critical factors for selection of electrokinetic treatment technologies are shown in Table 4-38.

Because electrokinetic treatment of metal-contaminated solid materials is in early stages of pilot testing, no action levels or more specific data requirements can be specified, as was done for other technologies in this document.

TABLE 4-38. SPECIFIC DATA NEEDS FOR ELECTROKINETIC TECHNOLOGIES

Factor Influencing Technology Selection[a]	Basis
Hydraulic conductivity	Technology applicable in zones of low hydraulic conductivity, particularly with high clay content.
Depth to water table	Technology applicable in saturated soils.
Areal extent of contamination	To assess electrode and recovery well placement.
Electroosmotic permeability	To estimate the rate of contaminant and water flow that can be induced.
Cation exchange capacity (CEC)	Technology most efficient when CEC is low.
Metals analysis	Technology applicable to acid soluble polar compounds, but not to nonpolar organics and acid insoluble metals.
Salinity	Technology most efficient when salinity is low. Chlorine gas can be produced by reduction of chloride ions at the anode.
Identification of half cell potentials	Characterizes possible reactions.

(a) Use hazardous substance list and site historical records to plan total waste analysis.

Source: U.S. EPA, 1991, EPA 540/2-91/009.

4.4 TREATMENT TECHNOLOGIES FOR GROUNDWATER AND WASTEWATER

Chapter 4 of the *Handbook: Stabilization Technologies for RCRA Corrective Actions* describes data collection, implementation, and technology application for groundwater pump-and-treat systems (U.S. EPA, 1991, EPA/625/6-91/026). A general review of methods to treat metals in groundwater is presented in *Resource Recovery Project Technology Characterization Interim Report* (MSE, 1993). Specific information on precipitation is available in *Precipitation of Metals from Ground Water* (NEESA, 1993). Bioremediation technologies are detailed in *Bioremediation of Metals* (Mattison, 1993). A summary of water treatment technologies is presented in Table 4-39. SITE Program technologies applicable to metal treatment are summarized in Appendix B (Tables B-2 and B-4).

TABLE 4-39. SUMMARY OF TREATMENT TECHNOLOGIES FOR METAL-BEARING WASTEWATER STREAMS

Process	*Applicable Waste Streams*	*Stage of Development*	*Performance*	*Residuals Generated*
		Physical Treatment Technologies		
Membrane separation	Aqueous wastestreams containing 10-20% metals depending on the technology used.	Demonstrated technology for many process and wastestreams.	Greater than 99% removal if properly used.	Concentrated brine requires treatment or disposal.
Liquid-liquid extraction	Aqueous, sludge, and solid wastes.	Limited use in hazardous waste field but widespread in mining and smelting industries.	Capable of yielding a solution that is 20 to 30 times more concentrated than feed.	Raffinate and regenerant stream may require post-treatment to remove residual extractant and metal.
Carbon adsorption	Aqueous wastestreams containing metal ions at low pH. Effective in treating chelated metals as well as metal cations.	Largely experimental with some field applications for treating hexavalent chromium and mercury-containing wastestreams.	Used as a primary treatment for removal of hexavalent chromium. With a Cr^{6+} influent concentration of 6 ppm, effluent concentration of Cr^{6+} remained below 0.05 ppm.	Spent carbon requires disposal or reactivation.
Ion exchange	Effective for treating dilute aqueous wastestreams as an end-of-pipe or polishing treatment.	Used in metal finishing and electroplating industries for recycling rinse solutions and concentrating waste metal solutions for efficient treatment.	Performance influenced by nature of functional group, ions available for exchange, and solution pH.	Regeneration solution requires treatment or disposal.
DeVoe-Holbein	Similar to ion exchange except capable of treating both dilute and concentrated solutions.	Newly developed process used in metal finishing industries, ore beneficiation, precious metals recovery, and chloralkali plants.	Performance reportedly shows high specificity; however, more data are needed to assess utility.	Regenerant required but has good potential for recycling because typically high in metals content.
Sorption on inactive biomass	Similar to ion exchange.	Several products commercially available.	Similar to ion exchange but more efficient at low contaminant concentrations.	Regeneration solution
Electrolytic treatment	Aqueous streams; high concentrations (greater than 1,000 ppm) are most efficiently removed.	Well developed and readily available from commercial vendors.	Performance varies greatly depending on the application and the particular electrolytic unit used; some units may remove over 90% of metals such as Cu, Pb, Zn, Au, Ag, and Cd.	Generally the metal is recovered in a usable form and no residual solids are generated.

TABLE 4-39. (continued)

Process	Applicable Waste Streams	Stage of Development	Performance	Residuals Generated
		Chemical Treatment Methods		
Precipitation (hydroxide & sulfide)	Aqueous streams; restrictions based on physical form, viscosity, and metal solubility.	Well-developed, reliable process, suitable for automatic control.	Heavy metals: Cd, Cu, Pb, Hg, Ni, Ag, and Zn removed to 0.01 to 0.5 mg/L.	Effluent stream will require further processing to remove and dispose of precipitated solids.
Coagulation/ flocculation	Aqueous streams; for ppb concentrations, two-stage process required; not readily applied to small, intermittent flows.	Well developed and readily available from commercial vendors.	Not considered a primary treatment but can achieve low residual levels.	Sludge requires secondary processing and disposal.
Reduction	Primarily, aqueous chrome-bearing wastestreams although sodium borohydride can treat most metals.	Well developed.	Chromium removal to 0.01 mg/L. Sodium borohydride able to remove Cu, Ni, Pb, Zn, Hg, Ag, Cd in the 0.01 to 1.0 mg/L range.	Effluent stream will require further processing to remove and dispose of reduced metal. Sodium borohydride introduces boron into the effluent stream.
Flotation	Aqueous streams containing 100 mg/L or less of metals. Restrictions based on physical form, oil and grease content.	Not fully developed for metals removal; primarily at pilot plant stage of development.	Heavy metals Pb, Cu, Zn, Cr^{3+} removed to 0.03 to 0.4 mg/L.	Requires post-treatment of metal-laden foam.
		Biological Treatment Methods		
Wetlands treatment	Constructed wetlands remove metals by partitioning or precipitation.	Pilot-scale	May be used as final treatment for low concentrations of heavy metals (10 mg/L or less).	Metals remain immobilized in wetland.
Bioreduction	Bioreduction	Bench-scale	Tested for conversion of mercury salts to metal and Cr(VI) reduction.	Reduced metal requires post-treatment for recovery or immobilization.
		Thermal Treatment Methods		
Evaporation	Aqueous wastes with low nonvolatile metals content, or wastes with highly volatile metals content.	Well developed and widely available.	Can effect high-level recovery of volatile metals or significant volume reduction of aqueous wastes.	Brine.
Crystallization	Primarily used for wastes from electroplating and pickling that contain high levels of acids, water, or low-molecular-weight organics.	Well developed. Often used in conjunction with evaporation.	Can effect high-level recovery.	Sludges.

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APPENDIX A

STABILITY REGION DIAGRAMS

Phase relationships can be presented in a variety of formats. Two formats that are particularly useful for evaluating the potential for metal mobility under conditions either present in situ or after treatment are diagrams of solubility versus pH and stability region diagrams such as Eh-pH diagrams. Solubility diagrams indicate the total dissolved metal concentration in equilibrium with a metal compound. Stability region diagrams show the thermodynamically stable chemical species in liquid form in multicomponent systems under all possible combinations of Eh-pH. Data from solubility and stability region diagrams can assist in interpreting and validating site characterization data, evaluating environmental fate and transport, and selecting treatment technologies.

Eh-pH diagrams are useful primarily for conceptual purposes in remediation, due to the complexity of the systems and the fact that the boundary lines are regions of transition rather than sharp delineations. Also, the diagram presupposes that the anionic species shown are in fact available in the system. Eh-pH diagrams give important information regarding the potential fixation of an element in soil. For example, below pH 2 and relatively high Eh, As will exist predominantly as H_3AsO_4 (Figure A-3). By utilizing Eh-pH diagrams, one can qualitatively estimate if soil conditions are conducive to the fixation. One must verify that the conditions assumed during the preparation of the diagrams are applicable to the conditions present at the site of concern. If the conditions are not applicable, one can construct a diagram that is applicable to a specific site (Dragun, 1988). The dotted lines in the Eh-pH diagrams represent the lower and upper limits of water stability.

Several diagrams are presented to illustrate the effects of oxidizing potential and pH on the stability of metal compounds. Figure A-1 illustrates the Eh-pH typical of water in a variety of natural settings (Garrels and Christ, 1965). All solubility and stability diagrams were prepared for this document by Professor H.H. Huang of Montana Tech, Butte, Montana, using the STABCAL computer model. The arsenate solubility graph (Figure A-2) uses data from Robins (1987) and MINTEQA2. Conditions are as follows: arsenate, 0.1 m; divalent metals, 0.15 m; trivalent metals, 0.1 m. Note that the solubility of arsenic in the As/Fe system is very sensitive to the ratio of arsenic to iron. For more detail, see Krause and Ettel (1989). The Eh-pH diagrams for arsenic, cadmium, chromium, lead, and mercury (Figures A-3 to A-7) use data from MINTEQA2. Conditions are as follows: metals, 0.001 m; S, 0.1 m; and carbonate, 0.1 m. The sulfur component included all sulfur species. The carbon component included only carbonate (i.e., no elemental carbon, acetate, etc.).

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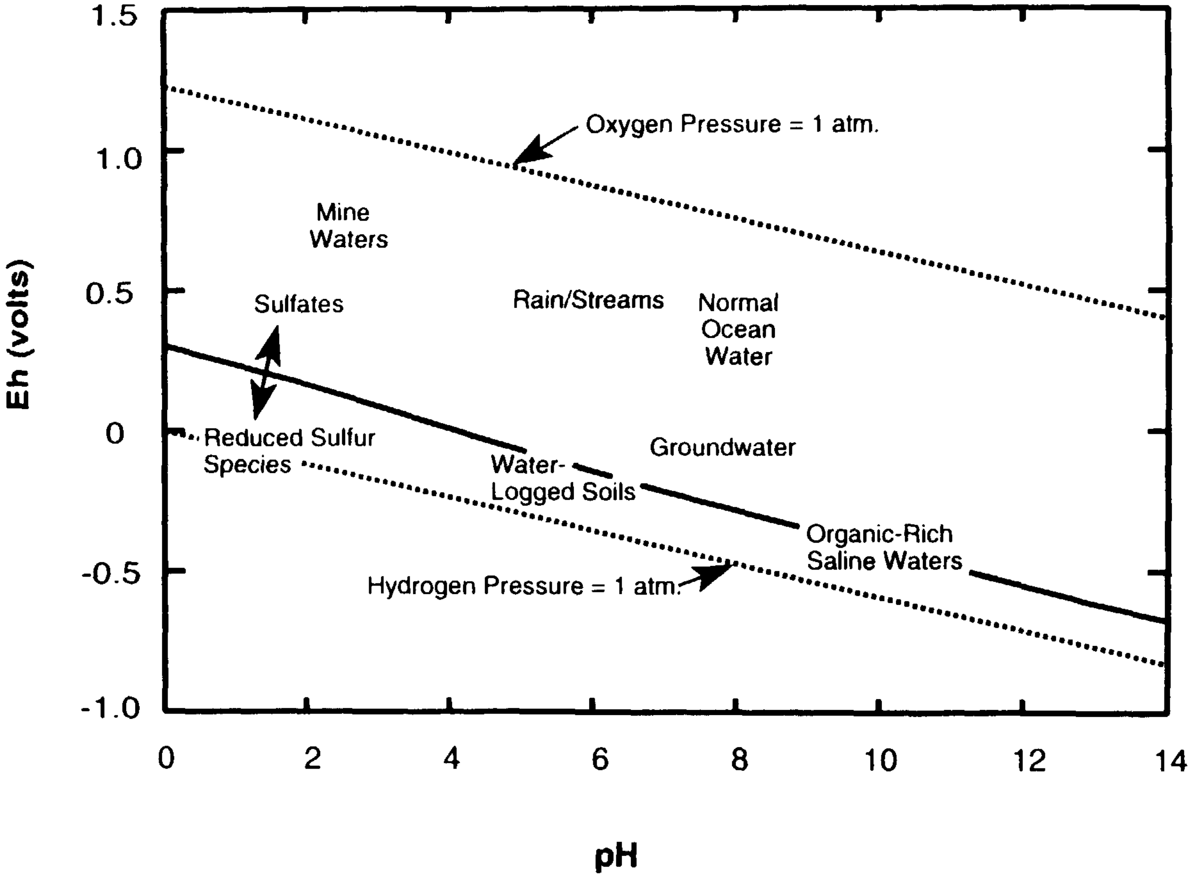

Figure A-1. Approximate position of some natural environments as characterized by Eh and pH.

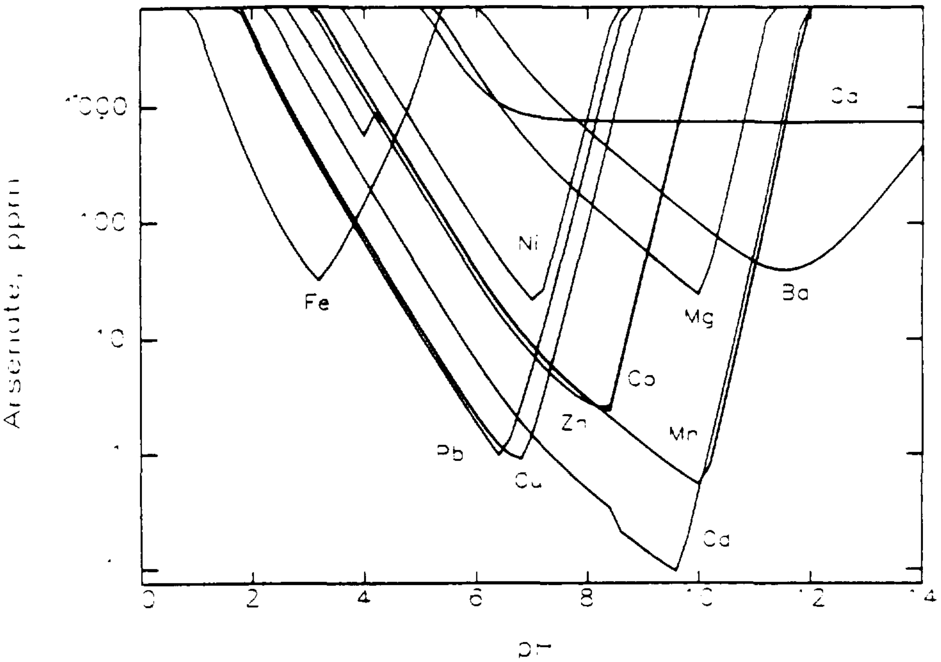

Figure A-2. Solubilities of metal arsenates.

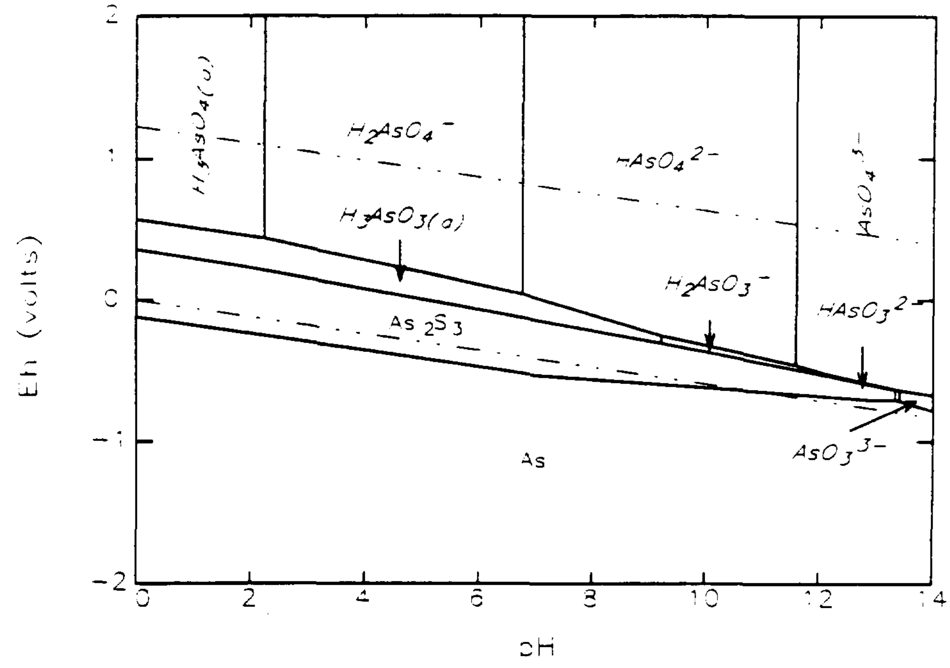

Figure A-3. Stability regions of arsenic species in the sulfur carbonate water system.

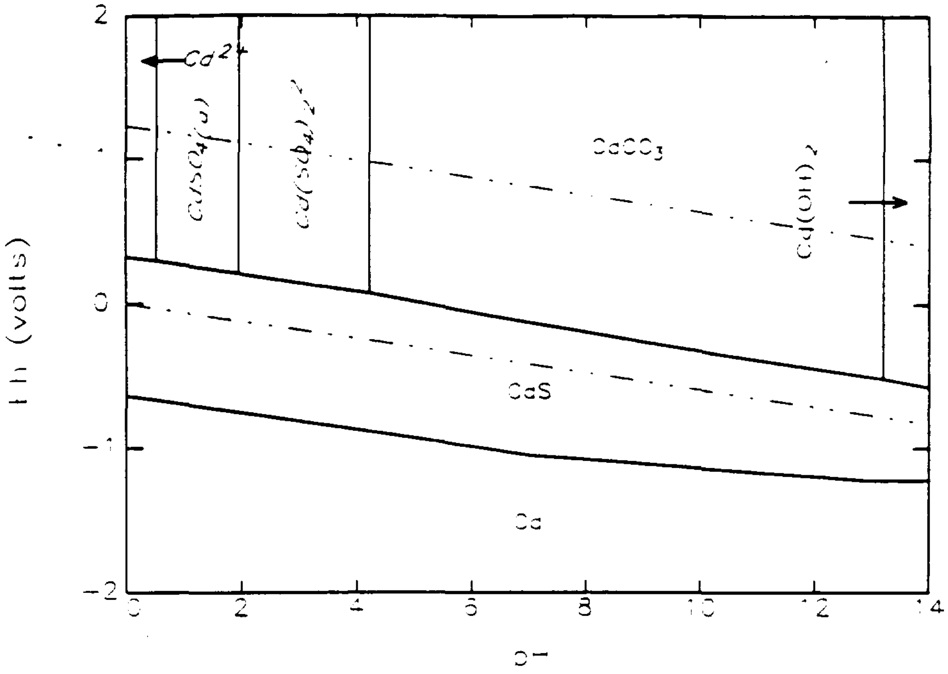

Figure A-4. Stability regions of cadmium species in the sulfur carbonate water system.

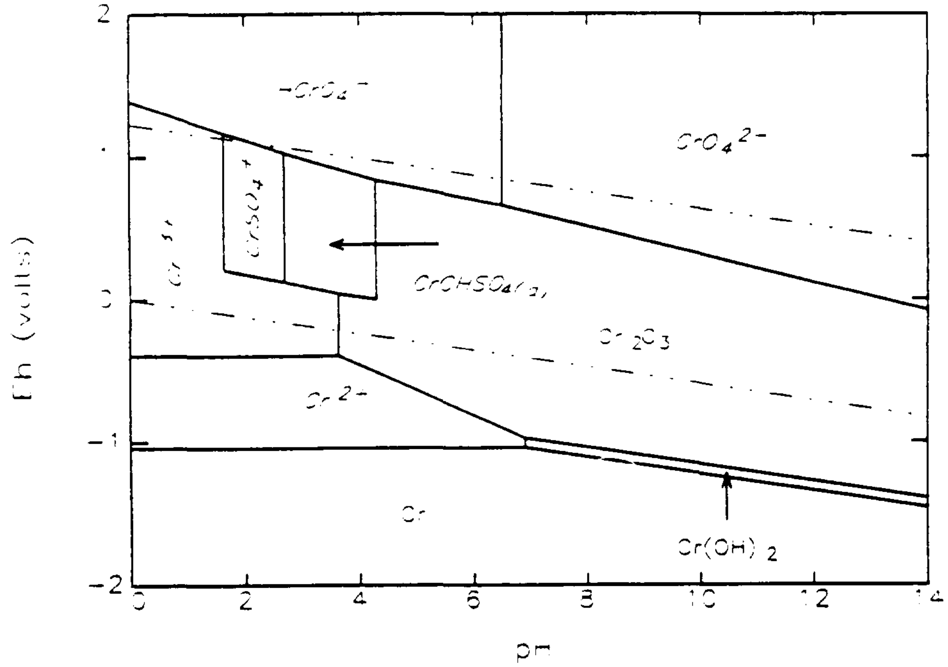

Figure A-5. Stability regions of chromium species in the sulfur carbonate water system.

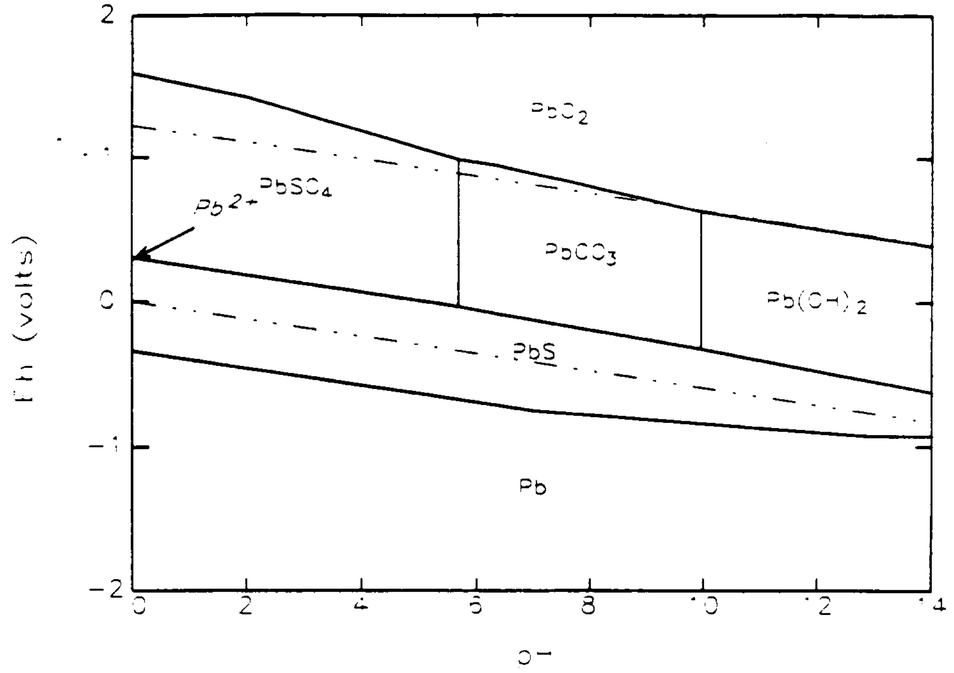

Figure A-6. Stability regions of lead species in the sulfur carbonate water system.

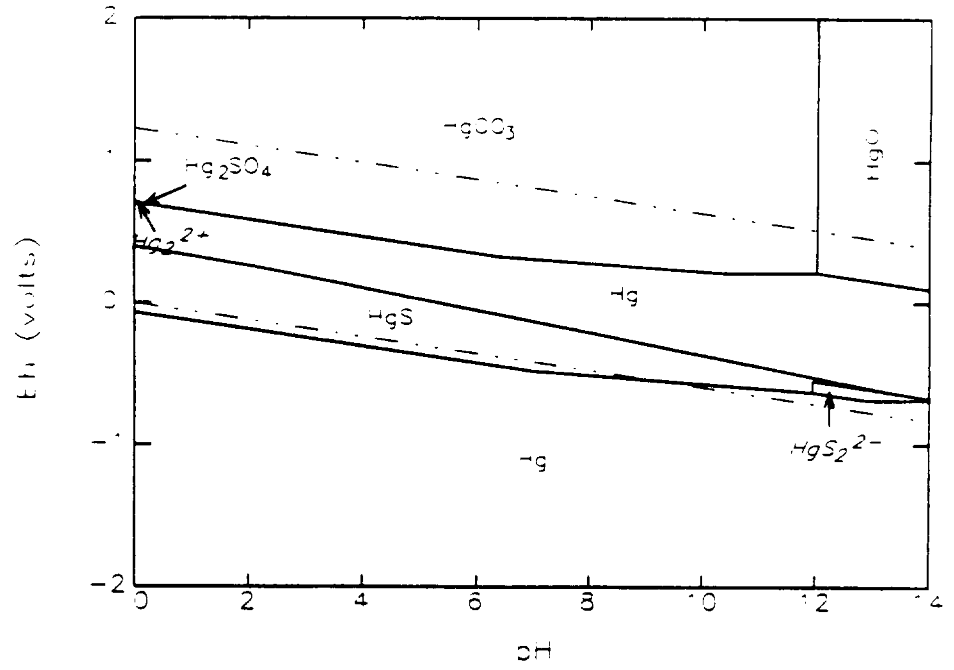

Figure A-7. Stability regions of mercury species in the sulfur carbonate water system.

APPENDIX B

SUMMARY TABLES OF SITE PROGRAM TECHNOLOGIES FOR METAL-CONTAMINATED SITES

The following tables summarize remediation technologies in the SITE Demonstration Program that involve metals. Tables B-1 and B-2 include metal-remediating technologies that are part of the Demonstrated Technologies Program, having undergone or scheduled a demonstration. Tables B-3 and B-4 summarize the technologies that are part of the Emerging Technologies Program. These tables can act as a quick reference for gaining a broad perception of the technologies available for metals remediation.

Technologies are listed alphabetically by the vendor's name. A brief technology summary presents an overview of the technology. The test location is listed separately because often it is a site located away from the vendor's location. Where available, the initial and treated contaminants and concentrations are given. Because the waste matrix is an important factor in determining the applicability of a technology, it is included. Reference documents are listed that can be accessed for more detail.

The SITE technology summary tables serve as a valuable tool in gaining familiarity with available technologies. The tables do not enumerate all available technologies, but they do provide a broad range of example treatment techniques.

TABLE B-1. SUMMARY TABLE OF SITE PROGRAM DEMONSTRATION TECHNOLOGIES FOR METAL-CONTAMINATED SOILS, SEDIMENTS, OR SLUDGES

Vendor/Technology	Technology Summary	Demonstration Site Location	Typical Applications	Matrix	Sources of Additional Information[(a)]
Babcock & Wilcox Co. Alliance, OH Cyclone Furnace	Contaminated solid is injected into a cyclone furnace to burn organics in high-ash content wastes. The ash residue exits the furnace as vitrified slag.	Alliance, OH	Non-specific inorganics 7000 ppm Pb, 1000 ppm Cd, 1500 ppm Cr	Soils, sludges, inorganic hazardous waste	AAR EPA/540/AR-92/017 DB EPA/540/MR-92/011 ETB EPA/540/F-92/010 TDS EPA/540/SR-92/017
Bergmann USA Gallatin, TN Soil and Sediment Washing Technology	Contaminated soil is separated according to density and grain size. Soil is then screened and mixed with water and chemical additives to form a slurry feed. The slurry feed flows to an attrition scrubbing machine, removing contaminated silts and clay.	Toronto, Ontario and Saginaw Bay Confined Disposal Facility, Saginaw, MI	Metals (i.e., Cd, Cr, Pb, Cu, Hg, Ni, Zn), radionuclides	Soil, sediments	DB EPA/540/MR-92/075
BioTrol, Inc. Chaska, MN Soil Washing System	Contaminated soil is treated in an intensive scrubbing circuit freeing contaminated fine particles. In addition, surficial contamination is removed from the coarse fraction by the abrasive scouring of the particles themselves.	MacGillis and Gibbs Superfund site in New Brighton, MN	As, Cu, Cr removed from 50-70%	Soil	DB EPA/540/M5-91/003 AAR EPA/540/5-91/003 TDS EPA/540/S5-91/003
Brice Env. Services Corp. Fairbanks, AK Soil Washing Plant	High attrition water washing partitions soil into fine and coarse fractions and remove metal contaminants from the coarse particles. Water is treated to remove contaminants and fine soil fraction is containerized.	Alaskan Battery Enterprises Superfund site in Fairbanks, AK	Radioisotopes and metals	Soil	DB EPA/540/MR-93/503 AAR EPA/540/AR-93/503
Chemfix Technologies, Inc. St. Rose, LA Solidification and Stabilization	Pozzolanic materials react with metal ions to produce a stable solid material. The metals are then immobilized in a silicate matrix.	Portable Equipment Salvage Co. in Clackamas, OR	Metals (i.e., Sb, As, Pb, Cd, Cr, Hg, Cu, Zn)	Solid wastes, soils, sludges, ashes	DB EPA/540/M5-89/011 AAR EPA/540/A5-89/011 TER EPA/540/5-89/011 TDS EPA/540/S5-89/011

(a) AAR = Applications Analysis Report; DB = Demonstration Bulletin; ETB = Emerging Technology Bulletin; SITE TP = SITE Technology Profiles EPA/540/R-92/077; TDS = Technology Demonstration Summary; TER = Technology Evaluation Report.
EPA Project Manager and vendor contacts are listed in SITE Technology Profiles.

TABLE B-1. (continued)

Vendor/Technology	Technology Summary	Demonstration Site Location	Typical Applications	Matrix	Sources of Additional Information[(a)]
Ensotech, Inc., Sun Valley, CA Chemical Oxidation/ Chemical Fixation	A trailer-mounted unit treats contaminated soil with a chemical fixing agent.	No site selected	Metals	Soils	SITE TP
Funderburk & Associates, Fairfield, TX (formerly HAZCON) Dechlorination and Immobilization	Hazardous waste is mixed with water and a Chloranan reagent. Cement is then added, solidifying the mixture and immobilizing metal contaminants.	Former Oil Processing Plant, Douglassville, PA	Metals	Soils, sludges, sediments	AAR EPA/540/A5-89/001 TER EPA/540/5-89/001a TDS EPA/540/S5-89/001
Geosafe Corp. Richland, WA In Situ Vitrification	An electric current is used to melt soil or sludge in situ. Electrodes placed in contaminated zones pass a current that generates melting temperatures. The soil results in a monolith with a silicate glass structure.	Demonstrated at 10 sites	Non-specific inorganics	Soil or sludge	SITE TP TC 540/R-94/520a
Horsehead Resource Development Co., Inc., Monaca, PA Flame Reactor	Wastes are processed in a flash-smelting system, the flame reactor. The waste is separated into slag and heavy metal-enriched oxide product (or in some cases, a metal alloy).	Material from the National Smelting and Refining Company Superfund site in Atlanta, GA	Metals (i.e., Zn, Pb, Cr, Cd, As, Cu, Ni)	Granular solids, soil, flue dusts, slags, and sludges	DB EPA/540/M5-91/005 AAR EPA/540/A5-91/005 TDS EPA/540/S5-91/005
International Waste Technologies/Geo-Con, Inc. Wichita, KS and Monroeville, PA In Situ Solidification and Stabilization	A deep soil mixing system mechanically mixes solidifying additives to contaminated soil. Solidifying additives from IWT and equipment from Geo-Con.	A PCB and metal-contaminated site in Hialeah, FL Contamination with metals was low: Cr, Cu, Pb, Zn	Inorganic metals, nonvolatile organics	Soil, sediments, sludge-pond bottoms	TDS EPA/540/S5-89/004 AAR EPA/540/A5-89/004 TER EPA/540/5-89/004a

(a) AAR = Applications Analysis Report; DB = Demonstration Bulletin; ETB = Emerging Technology Bulletin; SITE TP = SITE Technology Profiles EPA/540/R-92/077; TDS = Technology Demonstration Summary; TC = Technology Capsule; TER = Technology Evaluation Report.
EPA Project Manager and vendor contacts are listed in SITE Technology Profiles.

TABLE B-1. (continued)

Vendor/Technology	Technology Summary	Demonstration Site Location	Typical Applications	Matrix	Sources of Additional Information[a]
MAECORP Inc., Chicago, IL MAECTITE Treatment Process	A proprietary powder is blended with a lead-contaminated material. A reagent is added to this mixture to create insoluble mineral crystals.	Sioux Falls, SD	Lead	Soil, sludge, baghouse dusts	SITE TP
Ogden Env. Services, Houston, TX Circulating Bed Combustor	Waste is fed into the chamber of the Circulating Bed Combustor. A highly turbulent combustion zone mixes the waste and produces a uniform temperature. Metals are incorporated in slag.	pilot-scale demonstration at Ogden's Research Facility in San Diego, CA	Metals	Soil, liquids, slurries, sludges	DB EPA/540/MR-92/001 TER EPA/540/R-92/001
Recycling Sciences International, Inc., Chicago, IL Desorption and Vapor Extraction System	Contaminated materials are mixed with hot air which forces water and contaminants into vapor phase. The vapors are then processed in a gas treatment system.	No site selected	Volatile inorganics	Soils, sediments, and sludges	SITE TP
Remediation Technologies Inc., Concord, MA High Temperature Thermal Processor	Waste is fed into the system where a counter-rotational screw conveyor moves waste through the thermal processor. A molten salt eutectic serves as the heat transfer medium.	Proposed site at the Niagara-Mohawk Power Company in Harbour Point, NY	Mercury	Soils, sludges, sediment	SITE TP
Retech, Inc., Ukiah, CA Plasma Arc Vitrification	Waste material is fed into a centrifuge where it is heated by a plasma torch. The inorganic material is reduced to a molten phase that is discharged as a homogeneous, glassy slag.	Component Development and Integration Facility of the U.S. DOE in Butte, MT	Metals	Soil, sludge	DB EPA/540/M-91/007 AAR EPA/540/A5-91/007 TDS EPA/540/S5-91/007

(a) AAR = Applications Analysis Report; DB = Demonstration Bulletin; ETB = Emerging Technology Bulletin; SITE TP = SITE Technology Profiles EPA/540/R-92/077; TDS = Technology Demonstration Summary; TER = Technology Evaluation Report.
EPA Project Manager and vendor contacts are listed in SITE Technology Profiles.

TABLE B-1. (continued)

Vendor/Technology	Technology Summary	Demonstration Site Location	Typical Applications	Matrix	Sources of Additional Information[a]
Risk Reduction Engineering Laboratory, Cincinnati, OH Volume Reduction Unit	The process includes soil handling and conveying, soil washing and coarse screening, fine particle separation, flocculation/clarification, water treatment, and utilities.	Escambia Wood Treating Company, Pensacola, FL	Metals	Soils	DB EPA/540/MR-93/508 AAR EPA/540/AR-93/508
Risk Reduction Engineering Laboratory, Cincinnati, OH Debris Washing System	A basket of debris is placed in a tank where it is sprayed with an aqueous detergent. High-pressure water jets then blast contaminants from the debris.	Scheduled for the EPA's Evaluation Facility in Cincinnati, OH	Non-specific inorganics (i.e., Pb)	Metallics, masonry, other solid debris	TER EPA/540/5-91/006a
Risk Reduction Engineering Laboratory, Cincinnati, OH Hydraulic Fracturing	Water is injected into a borehole. The water pressure is raised to a level where it begins creating subsurface fractures. These fractures create pathways for vapors and fluids.	No full-scale site selected	Non-specific inorganics	Soil, groundwater	SITE TP
S.M.W. Seiko, Inc., Hayward, CA In Situ Solidification and Stabilization	Hollow augers mounted on a crawler-type base machine mix and inject solidification and stabilization reagents into contaminated soils in situ.	no site selected	Metals	Soils	SITE TP
Separation and Recovery Systems, Inc., Irvine, CA SAREX Chemical Fixation Process	Contaminated material is excavated and neutralized. The material is mixed with reagents to chemically and thermally stabilize contaminants.	No site selected	Low concentration metals	Sludges, soils	SITE TP

(a) AAR = Applications Analysis Report; DB = Demonstration Bulletin; ETB = Emerging Technology Bulletin; SITE TP = SITE Technology Profiles EPA/540/R-92/077; TDS = Technology Demonstration Summary; TER = Technology Evaluation Report.
EPA Project Manager and vendor contacts are listed in SITE Technology Profiles.

TABLE B-1. (continued)

Vendor/Technology	Technology Summary	Demonstration Site Location	Typical Applications	Matrix	Sources of Additional Information[(a)]
Silicate Technology Corp., Scottsdale, AZ Solidification and Stabilization Treatment	Contaminated material is pretreated, separated then fed into a mixer where a predetermined amount of reagent is added. These reactions result in the formation of insoluble chemical compounds.	Selma Pressure Treating wood-preserving site in Selma, CA	Metals	Soils, sluges, wastewaters	DB EPA/540/MR-92/010 AAR EPA/540/AR-92/010
Solidtech, Inc. Houston, TX Solidification and Stabilization	Contaminated waste is collected, screened, and mixed with a variety of substances rendering a solidified mass.	Imperial Oil Co./Champion Chemical Co. Superfund site in Morganville, NJ	Metals, non-specific inorganics	Soils, sludges	DB EPA/540/M5-89/005 AAR EPA/540/A5-89/005 TER EPA/540/5-89/005 TDS EPA/540/S5-89/005
Sonotech, Inc. Atlanta, GA Frequency Tunable Pulse Combustion System	The frequency tunable combustion system is applied to the incineration of wastes. The system promotes complete mixing along with heat and mass transfer, increasing the operational efficiency.	Scheduled for the EPA's Incinerator Research Facility in Jefferson, AK	Inorganics	Soils, or any material which can be treated in an incinerator	SITE TP
Texaco Syngas, Inc., White Plains, NJ Entrained-Bed Desorption	A slurry waste fee is passed through a gasifier which produces a synthesis gas. Metal contaminants are immobilized in a glass-like slag.	Completed at Texaco's Montebello Research Laboratory, S. Elmonte, CA	Non-specific inorganics	Soils, sludges, sediments	SITE TP
TEXAROME, Inc. Leakey, TX Solid Waste Desorption	Superheated steam is used as a stripping gas to treat contaminated solids. The gas may be condensed and decanted to remove contaminants.	No site selected.	Volatile inorganics	Soils, sludges, sediments	SITE TP
Toronto Harbour Commission, Toronto, Canada Soil Recycling	Three technologies are used in series to treat contaminants: soil washing, metal dissolution, and chemical hydrolysis.	A site within the Toronto Port Industrial District, Toronto, Ontario	Non-specific inorganics	Soils	DB EPA/540/MR-92/015

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EPA Project Manager and vendor contacts are listed in SITE Technology Profiles.

TABLE B-1. (continued)

Vendor/Technology	Technology Summary	Demonstration Site Location	Typical Applications	Matrix	Sources of Additional Information[(a)]
WASTECH, Inc. Oak Ridge, TN Solidification and Stabilization	Waste is excavated, then mixed with a proprietary agent and cementitious materials.	Robins Air Force Base in Warner Robins, GA	Non-specific inorganics, radionuclides	Soils, sludges, liquid wastes	SITE TP

(a) AAR = Applications Analysis Report; DB = Demonstration Bulletin; ETB = Emerging Technology Bulletin; SITE TP = SITE Technology Profiles EPA/540/R-92/077; TDS = Technology Demonstration Summary; TER = Technology Evaluation Report.
EPA Project Manager and vendor contacts are listed in SITE Technology Profiles.

TABLE B-2. SUMMARY TABLE OF SITE PROGRAM DEMONSTRATION TECHNOLOGIES FOR METAL-CONTAMINATED WATER

Vendor/Technology	Technology Summary	Demonstration Site Location	Typical Applications	Matrix	Sources of Additional Information[(a)]
Andco Env. Processes Inc. Amherst, NY Electrochemical In Situ Chromate Reduction and Heavy Metal Immobilization	This process uses electrochemical reactions to generate ions for the removal of chromium and other metals from the groundwater.	No site selected	Hexavalent chromium 1-50 ppm, and other heavy metals 2-10 ppm (Zn, Cu, Ni, Pb, Sb)	Groundwater	SITE TP
Bio-Recovery Systems Inc. Las Cruces, NM Biological Sorption	A contaminated solution is passed through an algae system to sorb metals. The metals can then be removed from the algae sorb with reagents.	Tested in 1989 Oakland, CA	Metals	Groundwater, process wastewaters	ETB EPA/540/5-90/005a
Chemical Waste Management Inc., Geneva, IL PO*WW*ER Technology	Wastewater is vaporized to concentrate contaminants in a brine. Contaminant vapors are then oxidized and destroyed, or treated in a scrubber.	Chemical Waste Management's pilot facility in Lake Charles, LA	Radioactive isotopes and metals	Industrial and hazardous wastewater	AAR EPA/540/AR-93/506
Colorado Dept. of Health Denver, CO Wetlands-Based Treatment	A man-made wetland ecosystem uses natural geochemical and biological processes to remove metals. Metals are removed by filtration, ion exchange, adsorption, absorption, and precipitation.	Proposed site at the Burleigh Tunnel near Silver Plume, CO	Metals from acid mine drainage	Influent waters	SITE TP
Dynaphore, Inc. Richmond, VA FORAGER Sponge	Wastewater is passed through a cellulose sponge with an amine-containing polymer that has an affinity for metal ions. The absorbed ions can then be eluted from the sponge, or the sponge can be incinerated or dried depending on preferred means of disposal.	Proposed site at the NL Industries site in Pedricktown, NJ	Various metals at ppm or ppb concentrations	Industrial effluent, municipal sewage, process streams, acid mine drainage waters	SITE TP

(a) AAR = Applications Analysis Report; DB = Demonstration Bulletin; ETB = Emerging Technology Bulletin; SITE TP = SITE Technology Profiles EPA/540/R-92/077; TDS = Technology Demonstration Summary; TER = Technology Evaluation Report.
EPA Project Manager and vendor contacts are listed in SITE Technology Profiles.

TABLE B-2. (continued)

Vendor/Technology	Technology Summary	Demonstration Site Location	Typical Applications	Matrix	Sources of Additional Information[a]
E.I. Dupont de Nemours and Co. and Oberlin Filter Co., Newark, DE and Waukesha, WI Membrane Microfiltration	Solid particles are removed from liquid wastes by passing them through a microfiltration system, leaving a filter cake containing the contaminants.	Palmerton Zinc Superfund site in Palmerton, PA	Metals at concentrations <5000 ppm (i.e., Cd, Pb, Zn)	Wastewater	AAR EPA/540/A5-90/007 TER EPA/540/5-90/007 DB EPA/540/M5-90/007 TDS EPA/540/S-90/007
EPOC Water Inc., Fresno, CA Precipitation, Microfiltration, and Sludge Dewatering	Contaminated water is treated to precipitate metals. The stream is then dewatered in a tubular filter press. Soils can be treated by acid leaching of metals followed by precipitation and filtration.	Iron Mountain Superfund site at Redding, CA	Metals	Wastewater, soil, or sludge	SITE TP
Filter Flow Technology, Inc., League City, TX Heavy Metals and Radionuclide Sorption Method	Contaminated water is pumped to a mixing vessel for pH adjustment and chemical treatment. The mixture is then passed through the Colloid Sorption Unit, a specially designed filtration apparatus.	No site selected	Metals and radionuclides	Groundwater, pond water, industrial wastewater	SITE TP
GEOCHEM, A Division of Terra Vac, Lakewood, CO In Situ Remediation of Chromium in Groundwater	Contaminated groundwater is pumped to the surface and treated using conventional methods. Next a reductant is added and the treated water is reinjected. This allows for in situ reduction and subsequent fixation of residual chromium.	Will be demonstrated at the Valley Wood Treating site in Turlock, CA	Primarily hexavalent chromium, in addition (i.e., U, As, Se)	Groundwater	SITE TP
Hazardous Waste Control, Fairfield, CT NOMIX Technology	A solidifying compound is added to the waste fluid to promote solidification. The process requires no mixing between the waste and the solidifying compound.	No site selected	Metal compounds	Primarily aqueous solutions of drum waste, minor spills in situ, waste lagoons	SITE TP

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EPA Project Manager and vendor contacts are listed in SITE Technology Profiles.

TABLE B-2. (continued)

Vendor/Technology	Technology Summary	Demonstration Site Location	Typical Applications	Matrix	Sources of Additional Information[(a)]
Rochem Separation Systems, Inc., Torrance, CA Rochem Disc Tube Module System	A reverse osmosis membrane system is used in conjunction with an ultrafiltration process to remove contaminants.	Planned for Casmalia Resources in Santa Barbara County, CA	Non-specific inorganics	Wastewaters	SITE TP
TechTran Env. Inc., Houston, TX Combined Chemical Precipitation, Physical Separation, and Binding Process	A contaminated water stream is combined and mixed with the proprietary RHM-100 powder along with a complex mixture of oxides, silicates, and other reactive binding agents.	Scheduled for a uranium mine in Texas	Metals and radioactive isotopes	Wastewater, groundwater, soils, sludges	SITE TP
QUAD Env. Technologies Corp., Northbrook, IL Chemtact Gaseous Waste Treatment	A gas scrubber removes contaminants from gaseous waste-streams. This process produces low volumes of liquid residuals which are treated by conventional techniques.	No site selected	Non-specific inorganics	Gaseous wastestream	SITE TP

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EPA Project Manager and vendor contacts are listed in SITE Technology Profiles.

TABLE B-3. SUMMARY TABLE OF SITE PROGRAM EMERGING TECHNOLOGIES FOR METAL-CONTAMINATED SOILS, SEDIMENTS, OR SLUDGES

Vendor/Technology	Technology Summary	Test Location	Typically Applicable Contaminants	Matrix	Sources of Additional Information[(a)]
Allis Mineral Systems, Inc. Oak Creek, WI Pyrokiln Thermal Encapsulation Process	The process modifies conventional rotary kiln hazardous waste incineration by adding fluxing agents to the waste to promote incipient slagging or "thermal encapsulating."	Test Center in Oak Creek, WI	Metals (Sb, As, Ba, Be, Cd, Cr, Cu, Pb, Ni, Se, Ag, Ta, Zn)	Soils, sludges	SITE TP
Babcock & Wilcox Co., Alliance, OH Cyclone Furnace	Contaminated solid is injected into a cyclone furnace to burn organics in high-ash-content wastes. The ash residue exits the furnace as vitrified slag.	Alliance, OH	Inorganics (7000 ppm Pb, 1000 ppm Cd, and 1500 ppm Cr)	Soils, sludges, in-organic hazardous wastes	ETB EPA/540/F-92/010
Battelle Memorial Institute, Columbus, OH In Situ Electroacoustic Soil Decontamination	An electric potential is applied to soils to displace ions to their respective electrodes. Acoustic fields increase leaching and dewatering.	Columbus, OH	Metals (i.e., Zn, Cd)	Fine-grained clay soils	SITE TP
Center for Hazardous Materials Research, Pittsburgh, PA Acid Extraction Treatment System	A soil washing process that uses HCl (pH of 2) for extraction of contaminants. Following extraction the soil is rinsed, neutralized, and dewatered.	Pittsburgh, PA	Metals (i.e., As, Cd, Cr, Cu, Pb, Ni, Zn)	Soils	SITE TP
Center for Hazardous Materials Research, Pittsburgh, PA Lead Smelting	Contaminated mixtures are added to reverberatory and blast furnaces which heat the mixtures and remove the lead by a combination of melting, reduction, and volatilization.	Exide secondary lead smelter in Reading, PA	Lead	Lead-bearing materials	SITE TP
Center for Hazardous Materials Research, Pittsburgh, PA Organics Destruction and Metals Stabilization	Elemental sulfur is combined with a contaminated solid in a process which stabilizes metals and metal ions. Treatment involves mixing and heating.	Pittsburgh, PA	Metals	Soils, sediments	SITE TP

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TABLE B-3. (continued)

Vendor/Technology	Technology Summary	Test Location	Typically Applicable Contaminants	Matrix	Sources of Additional Information[a]
COGNIS, Inc., Santa Rosa, CA Biological/Chemical Treatment	Treatment of soil for both organics and metals, can be performed simultaneously. Metals are exposed to a leachant which is then treated for removal of metals. Following metal removal, organics are treated by biological action.	Santa Rosa, CA	Metals (Cd, Cu, Hg, Pb, Zn)	Soils	SITE TP
COGNIS, Inc., Santa Rosa, CA Chemical Treatment	Contaminated material is dry screened and exposed to a leachant which removes metals. Metals can then be recovered through liquid ion exchange, resin ion exchange, or reduction.	Santa Rosa, CA	Metals, particularly lead	Soils, sludges, sediments	SITE TP
Davy Research and Development, Ltd., Cleveland, England Chemical Treatment	Contaminated soils are screened and leached. Contaminants are removed from the leachant in a resin-in-pulp or a carbon-in-pulp system using ion exchange resins or activated carbon, respectively.	site selection underway	Metals (i.e., Cu, Cr, Zn, Hg, As)	Soils, sediments, dredgings, solid residues	SITE TP
Electrokinetics, Inc., Baton Rouge, LA Electrokinetic Remediation	Electrodes and pore fluids are placed in a contaminated area. An acid front is created by electrolytic action to desorb contaminants. The contaminants migrate to the electrodes for recovery.	Baton Rouge, LA	Metals or radionuclides (i.e., Pb, As, Cd, Cr, Cu, Ni, Zn, U)	Soils, sediments	SITE TP
Energy and Environmental Research Corporation, Irvine, CA Hybrid Fluidized Bed System	Contaminated soils are heated on a spouted bed. Clean soil is then removed and off-gases are treated.	Irvine, CA	Volatile inorganics	Soils, sludges	SITE TP
Ferro Corporation Independence, OH Waste Vitrification Through Electric Melting	An electric meter vitrifies contaminated materials converting them into oxide glasses.	Independence, OH	Non-specific inorganics	Soils, sludges, sediments	SITE TP

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EPA Project Manager and vendor contacts ar[illegible]ed in SITE Technology Profiles.

TABLE B-3. (continued)

Vendor/Technology	Technology Summary	Test Location	Typically Applicable Contaminants	Matrix	Sources of Additional Information[(a)]
IT Corporation, Knoxville, TN Batch Steam Distillation and Metal Extraction	Waste soil slurried in water is heated to 100°C to vaporize the VOCs. Metals are then removed by HCl extraction. Acid extract is treated in a bath distillation system, where the acid is recovered and a metal concentrate sludge is drawn off.	Knoxville, TN	Metals	Soils	SITE TP
IT Corporation, Knoxville, TN Mixed Waste Treatment Process	The process begins with thermal treatment to remove volatiles. Inorganics are removed by gravity separation, chemical precipitation, and chelant extraction.	Pilot scale at Johnston Atoll in the South Pacific	Non-specific inorganics, radioactive materials	Soils	SITE TP
Montana College of Mineral Science & Technology, Butte, MT Campbell Centrifugal Jig	Slurried material is fed into the Campbell Centrifugal Jig. Heavy contaminants pass through the jig bed to become concentrates, while particles with a lower specific gravity are flushed off the jig head as tailings.	Butte, MT	Metals	Soils	SITE TP
New Jersey Institute of Technology, Newark, NJ GHEA Associates Process	Soil is excavated, washed with surfactants, and rinsed. Contaminants are separated from the surfactants by desorption and are isolated as concentrate.	Newark, NJ	Metals	Soils, sludges, sediments, groundwater, surface water, point source industrial effluent	SITE TP
PSI Technology Company, Andover, MA Metals Immobilization and Decontamination of Aggregate Solids	Contaminated material is incinerated causing metals to concentrate in the fly ash. The fly ash is then treated with a sorbent to immobilize the metals.	Andover, MA	Metals (particularly As, Cd, Cr, Pb, Ni, and Zn)	Soils, sediments, sludges	SITE TP

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EPA Project Manager and vendor contacts are listed in SITE Technology Profiles.

TABLE B-3. (continued)

Vendor/Technology	Technology Summary	Test Location	Typically Applicable Contaminants	Matrix	Sources of Additional Information[a]
Vortec Corporation, Collegeville, PA Oxidation and Vitrification Process	Contaminated soil is introduced to a precombustor where moisture vaporizes and organics oxidize. The material then moves to a fossil-fueled combustor where it is heated to form a molten glass product. This end product is tapped into a slag tank.	Collegeville, PA	Metals (As, Cd, Cr, Cu, Pb, Ni, Zn)	Soils, sediments, sludges, mill tailings	SITE TP
Warren Spring Laboratory (changed to National Environmental Technology Centre) Hertsfordshire, United Kingdom Physical and Chemical Treatment	Feed material is screened, scrubbed with water, and sized into 10-50 mm, 1-10 mm, and <1 mm. Less than 1 mm fraction undergoes removal of clays (<0.1 mm), density separation, magnetic separation, fresh flotation, or multi-gravity separator separation. Several clean and contaminated streams result. Water is treated and recycled	Hertsfordshire, United Kingdom (Don facility)	Organics and metals As, Cd, Zn, Pb, and cyanide	Soils, sediments, sludges	SITE TP

(a) AAR = Applications Analysis Report; DB = Demonstration Bulletin; ETB = Emerging Technology Bulletin;
SITE TP = SITE Technology Profiles EPA/540/R-92/077; TDS = Technology Demonstration Summary;
TER = Technology Evaluation Report.
EPA Project Manager and vendor contacts are listed in SITE Technology Profiles.

TABLE B-4. SUMMARY TABLE OF SITE PROGRAM EMERGING TECHNOLOGIES FOR METAL-CONTAMINATED WATER

Vendor/Technology	Technology Summary	Test Location	Typically Applicable Contaminants	Matrix	Sources of Additional Information[(a)]
Atomic Energy of Canada, Ltd. Chalk River, Ontario Chemical Treatment and Ultrafiltration	Selective removal of metal contaminants from water occurs through the use of prefilters, two banks of filters, and polyelectrolyte addition.	Chalk River Laboratories, and a uranium mine tailings site in Ontario	Metals (i.e., Cd, Pb, Hg, U, Mn, Ni, Cr, Ag)	Groundwater, leachate, surface runoff, industrial effluent	ETB EPA/540/F-92/002
Bio-Recovery Systems, Inc., Las Cruces, NM Biological Sorption	A contaminated solution is passed through an algae-based sorbent system. The algae matrix becomes saturated with metals which can then be removed with reagents.	A hazardous waste site in Oakland, CA	Metals	Groundwater, process wastewaters	ETB EPA/540/F-92/003
Colorado School of Mines, Golden, CO Wetlands-Based Treatment	Contaminated waters flow into the zones of a man-made wetland ecosystem. The metals are removed by filtration, ion exchange, adsorption, absorption, and precipitation.	Proposed for the Burleigh Tunnel near Silver Plume, CO	Metals typically acidic	Acid mine drainage	ETB EPA/540/F-92/001
Electro-Pure Systems, Inc., Amherst, NY Alternating Current Electrocoagulation Technology	Highly charged polyhydroxide aluminum species are introduced to a contaminated solution. An alternating current field is applied to form a flocculant to trap contaminants.	Amherst, NY	Metals	Aqueous solutions and suspensions	ETB EPA/540/F-92/011
Montana College of Mineral Science & Technology, Butte, MT Air-Sparged Hydrocyclone	The air-sparged hydrocyclone uses a porous air cylinder with a traditional cyclone header to separate contaminated materials by flotation.	Butte, MT	Low concentration metals, generally sulfide materials	Aqueous solutions	SITE TP
University of South Carolina, Columbia, SC In Situ Mitigation of Acid Water	During mine construction, surface depressions are installed to collect runoff. These funnel and divert the water into the waste rock dump through chimneys constructed of limestone. This alkaline source material serves to buffer acids in the water.	University of South Carolina	Most metals	Acid drainage	SITE TP

(a) ETB = Emerging Technology Bulletin; SITE TP = SITE Technology Profiles EPA/540/R-92/077.
EPA Project Manager and vendor contacts are listed in SITE Technology Profiles.

TABLE B-4. (continued)

Vendor/Technology	Technology Summary	Test Location	Typically Applicable Contaminants	Matrix	Sources of Additional Information[a]
University of Washington, Seattle, WA Adsorptive Filtration	A contaminated solution is adjusted to a pH of 9 to 10 and passed through a column of sand with adsorbent coating. When adsorbed capacity is reached, contaminants may be recovered in concentrate with an acid.	Seattle, WA	Metals (Cd, Cu, Pb at 0.5 ppm)	Aqueous wastestreams	ETB EPA/540/F-92/008
Western Product Recovery Group, Inc. Houston, TX CCBA Physical and Chemical Treatment	Contaminated material is mixed with clays and formed into pellets. The pellets are fired in a rotary kiln where silica in the clay bonds to metals to form a metal silicate product.	Houston, TX	Metals	Wastewaters, sludges, sediments, soils	SITE TP

(a) ETB = Emerging Technology Bulletin; SITE TP = SITE Technology Profiles EPA/540/R-92/077. EPA Project Manager and vendor contacts are listed in SITE Technology Profiles.

APPENDIX C

SUMMARY OF METAL-CONTAMINATED WASTE TREATMENT TECHNOLOGY VENDORS SHOWN IN VISITT VERSION 3.0 (1994)

Notes:

1. Inclusion in the U.S. Environmental Protection Agency's VISITT (Vendor Information System for Innovative Treatment Technologies) database does not mean that the EPA approves, recommends, licenses, certifies, or authorizes the use of any of the technologies. Nor does EPA certify the accuracy of the data. Listing in this database means only that the vendor has provided information on a technology that EPA considers to be eligible.

2. VISITT is updated periodically. For information on availability and updates, call the VISITT Hotline at (800) 245-4505 or (703) 883-8448.

3. This Appendix includes only those companies that have identified metals as the contaminant of treatment, except for the Materials Handling/Physical Separation Technology category which is not contaminant-specific.

TABLE C-1. SUMMARY OF METAL-CONTAMINATED WASTE TREATMENT TECHNOLOGY VENDORS SHOWN IN VISITT VERSION 3.0

Technology	Vendor	Cost ($/ton)(a)	Media	Contaminants	Untreated Conc. Range (mg/kg)(a)	Treated Conc. Range (mg/kg)(a)	Scale of Operation
Vitrification	B&W-Nuclear Environmental Services, Inc. (ex situ)	460-530/wet ton	Soil	Uranium	30-150 pCi/g	< 10-30 pCi/g	Pilot
	EET Corp. (ex situ)	No Data	Sludge	Cr	500 ppm	0.015-0.054 ppm	Pilot
				Ni	100-500 ppm	0.015-0.039 ppm	
				Pb	250-500 ppm	0.05-0.219 ppm	
				Cd	15-500 ppm	0.015-0.339 ppm	
				Ag	200-500 ppm	Not Detected	
	Battelle Pacific NW Laboratories (ex situ)	50-300/wet ton	Soil	No Data	No Data	No Data	Bench
			Soil	Ba	0.76 ppm	<0.05 ppm	Pilot
				Cd	0.23 ppm	0.05 ppm	
				Pb	0.73 ppm	<0.05 ppm	
	Electro-Pyrolysis, Inc. (ex situ)	No Data	Soil, Slag, Sediment	Heavy metals	0-500	Not Detected	Pilot
	Geosafe Corp. (in situ)	300-500	Soil, Sediment	Hg	60 ppm	<0.1 ppm	Full
			Sludge	No Data	No Data	No Data	Full
	ReTech (ex situ)	600-1,200	Soil, Slag, Sludge	Cd	0.067	<0.039 mg/L	Pilot
				Cu	4.6	0.15 mg/L	
				Ni	0.22	<0.11 mg/L	
	Vortec Corp. (ex situ)	40-100	Slag, Off-Gas	Pb	8.4-14.1	<0.3-0.73	Pilot
				Cd	ND-8.9	Not Detected	
			Slag	As	3,000	No Data	Full
				Ba	3,000	No Data	
				Cd	3,000	No Data	

(a) Unless other units are stated with the value.

TABLE C-1. (continued)

Technology	Vendor	Cost ($/ton)[(a)]	Media	Contaminants	Untreated Conc. Range (mg/kg)[(a)]	Treated Conc. Range (mg/kg)[(a)]	Scale of Operation
Vitrification (cont)	Vortec Corp. (cont)	40-100	Slag (cont)	Cr	3,000	No Data	Full
				Pb	3,000	5	
				Cesium	3,000	No Data	
				Cerium	3,000	No Data	
			Soil (ex situ)	As	ND-274	Not Detected	Pilot
				Pb	ND-2,025	ND-0.087	
				Cd	ND-181	ND-0.008	
				Cr	ND-842	ND-0.063	
Soil Washing	Alternative Remedial Technologies, Inc. (ex situ)	85-225	Soil	Pb	500-1,000	90	Full
				Zn	6,040	90	
				CN	200-1,000	5	
				Cr	500-5,000	73	
				Ni	300-3,500	25	Full
				Cu	800-8,500	110	
				As	15-455	20	
				Cr	20-590	16	
	B&W-Nuclear Environmental Services, Inc. (ex situ)	6-12/ft^3	Soil	U	30-150 pCi/g	10-30 pCi/g	Pilot
	Bergman (ex situ)	75-125	Sediment	Cd	0.50	0.06	Pilot
				Cr	23.9	10.8	
				Hg	0.061	0.008	
				Ni	11.5	3.3	
				Pb	20.4	7.42	
				Zn	96.1	17.1	

(a) Unless other units are stated with the value.

TABLE C-1. (continued)

Technology	Vendor	Cost ($/ton)[a]	Media	Contaminants	Untreated Conc. Range (mg/kg)[a]	Treated Conc. Range (mg/kg)[a]	Scale of Operation
Soil Washing (cont)	Bergman (cont)	75-125	Soil, Sediment	Cu	9.2-42.2	13.8	Full
				Pb	63-127	23-82	
	Bio-Recovery	No Data	No Data	Pb	280-14,000	0.1-1.5	Bench
				Cu	190-9,500	0.1-4	
	Canonie	50-100	Soil, Sediment	No Data	No Data	No Data	Full
	Earth Decontaminators Inc. (ex situ)	110-170	Soil	Pb	2,700	5.8	Pilot
	Geochem	No Data	Soil	Pb	8,000 ppm	<30 ppm	Bench
	NUKEM	70-300	Soil, Sediment	Pb	500-700	200-240	Bench
				Hg	80-120	20-24	
	On-Site Technologies	40-120	Soil, Sediment	Cu	1.0-100	0.01-1.0	Full
				Pb	1.0-100	0.01-1.0	
	Scientific Ecology	100-300	Soil	As	250	20	Full
				Cr	150	15	
				Pb	12,000	500	
				Radium	3-21 pCi/g	4 pCi/g	
				Cu	1,000-2,000 ppm	100-250 ppm	Bench
				U	100-200	40-80	Pilot
				Hg	1,000-5,000	100-300	
	Tuboscope Vetco	30-200/yd^3	Soil	Radium Sulfate	50-225	2-5	Full
				Pb	3,300	204	
				Ba	2,000	200	
				Cr	1,000	250	
				Pb	500	100	

(a) Unless other units are stated with the value.

TABLE C-1. (continued)

Technology	Vendor	Cost ($/ton)[a]	Media	Contaminants	Untreated Conc. Range (mg/kg)[a]	Treated Conc. Range (mg/kg)[a]	Scale of Operation
Acid Extraction	Center for Hazardous Materials Research	60-160	Soil, Slag, Sludge, Sediment	Pb	900-30,000	500-1,000	Pilot
				Cd	200-2,000	20-100	
				Zn	1,000-30,000	50-1,000	
	COGNIS	100-200	Soil	Pb	1,000-100,000	50-50,000	Bench
				Zn	1,000-100,000	50-50,000	
				Hg	5,000-15,000	<50	
				Pb, Hg, Cu, Cd, Sb, Ag, Cr, Ni	500-86,000	30-300	Full
	Earth Treatment Technologies, Inc.	100-250	Soil	Pb	780-5,700 ppm	70-170 ppm	Bench
				Cu	2,000-7,300	50-180	
				Pb	470-130,000	ND-162	
				Hg	32-1,200	2-14	
				Hg-Soluble	32-1,200	ND-0.16	
				Ni	315-1,520	ND-2.2	
				Pb	1,000-4,900 ppm	ND-1.3 ppm	Full
				Cr	400-1,000 ppm	Not Detected	
				Cd	400-1,200	ND-1	
			Slag	Cu	500-2,200 ppm	10-28 ppm	Bench
	IT Corporation	No Data	Soil	Vanadium	27.8	0.8	Pilot
				As	8.5	<0.12	
				Ba	417	4.7	
				Cd	5.2	0.017	
				Cr	224	5.1	

(a) Unless other units are stated with the value.

TABLE C-1. (continued)

Technology	Vendor	Cost ($/ton)[a]	Media	Contaminants	Untreated Conc. Range (mg/kg)[a]	Treated Conc. Range (mg/kg)[a]	Scale of Operation
Acid Extraction (cont)	IT Corporation (cont)	No Data	Soil	Pb	2,300	7.8	Pilot
				Hg	1.2	0.8	
				Ag	3.3	<0.015	
				Zn	979	2.7	
Electrical Separation	Electrokinetics, Inc. (ex situ)	20-100/yd^3	Soil	Pb	500-130,000	20-50,000	Pilot
				U	1,000 pCi/g	10-90 pCi/g	
Magnetic Separation Treatment	S.G. Frantz Co., Inc. (ex situ)	60-6,000	Sediment	Heavy metals	No Data	No Data	Bench
			Slag	Plutonium	15,500-15,700	5,100-8,600	
			Soil, Sediment	Contaminating minerals	10,000-50,000	5-20	
			Soil, Sludge, Sediment	U	4,000-14,000	300-3,900	
Materials Handling/ Physical Separation	Canonie	100-150	Slag	Pb	100-200	ND-5	Full
			Slag	No Data	No Data	No Data	Bench
			Slag	No Data	No Data	No Data	Pilot
	ECOVA, Corp.	50-150	Sludge	No Data	No Data	No Data	Pilot
			Sludge	No Data	No Data	No Data	Full
	Microfluidics Corp. (ex situ)	No Data	Soil, Sludge	No Data	No Data	No Data	Pilot
	Onsite/Offsite Inc./Battelle	No Data	Sludge	No Data	No Data	No Data	Bench
	Portec, Inc. (in situ or ex situ)	20-200	Soil, Slag, Sludge, Sediment	No Data	No Data	No Data	Full
	Recra Environmental, Inc. (ex situ)	1-5	Soil, Slag, Sludge, Sediment	No Data	No Data	No Data	Full

(a) Unless other units are stated with the value.

TABLE C-1. (continued)

Technology	Vendor	Cost ($/ton)$^{(a)}$	Media	Contaminants	Untreated Conc. Range (mg/kg)$^{(a)}$	Treated Conc. Range (mg/kg)$^{(a)}$	Scale of Operation
Chemical Treatment-Other	DAVY Research & Development, Ltd. (ex situ)	No Data	Soil	As	1,204	112	Bench
				Cr	612	74	
				Pb	156	10	
				Hg	10-100	0.4-2.0	
				Zn	414	68	
	EPS Environmental, Inc.	No Data	Slag	Hg	0.022-0.697	ND-0.003	Full
	Integrated Chemistries, Inc.	0.2/ft^2	Slag	Cr	569	175	Full
	Viking Industries	0.05/gal	Sludge	Zinc Cyanide	8.14 mg/L	0.1 mg/L	Bench
				Nickel Cyanide	808 mg/L	3.4 mg/L	
				Cadmium Cyanide	605 mg/L	0.2 mg/L	
	ETUS, Inc. (in situ or ex situ)	20-50	Soil, GW, Sediment	As	1-5 ppm	0.001-0.005 ppm	Full
			Soil, Sludge	Organic Pb	5-200	0.01-1.0	Full
			Sludge	Ni	100-5,000	1.0-5.0	Full
			Soil, Slag, Sludge, GW, Sediment	Pb	10-10,000 ppm	0.01-5.0 ppm	Full
				Cr (VI and total)	100-10,000 ppm	0.1-2.0 ppm	Pilot
Slagging	Horsehead Resource Development Co.	150-300	Soil	Pb	118,000	2,100-8,900	Full
			Slag	Pb	48,200-61,700	1,560-11,400	Full
				Cd	356-512	<2.3-13.5	
			Sludge	Pb	8.2%	0.15%	Full
				Cd	0.7%	0.005%	

(a) Unless other units are stated with the value.

TABLE C-1. *(continued)*

Technology	Vendor	Cost ($/ton)[(a)]	Media	Contaminants	Untreated Conc. Range (mg/kg)[(a)]	Treated Conc. Range (mg/kg)[(a)]	Scale of Operation
Thermal Desorption	Hazen Research, Inc.	No Data	Soil, Slag, Off-gas, Sludge	Hg	1,000-300,000	0.001-0.023	Pilot
	Pittsburgh Mineral & Environmental Tech.	400-700	Slag, Sludge	Hg	4-25,000 ppm	0.05-1 ppm	Bench
			Soil	Hg	1,000-15,000 ppm	0.05-0.8 ppm	Pilot

(a) Unless other units are stated with the value.

METAL-TREATMENT VENDORS, ADDRESSES, AND CONTACTS

Alternative Remedial Technologies, Inc.
Michael J. Mann, P.E.
14497 North Dale Mabry Hwy.
Tampa, FL 33618
(813) 264-3506

B&W-Nuclear Environmental Services
L.P. Williams
2220 Langhorne Rd.
Lynchburg, VA 24501
(804) 948-4610

Battelle Pacific NW Laboratories
Chris Johnson
Battelle Blvd.
P.O. Box 999
Richland, WA 99352
(509) 372-2273

Bergmann
Richard P. Traver, P.E.
1550 Airport Rd.
Gallatin, TN 37066-3739
(615) 452-5500

Bio-Recovery
Godfrey A. Crane
2001 Cooper Ave.
Las Cruces, NM 88005-7105
(505) 523-0405

Canonie
Alistair H. Montgomery
94 Iverness Terrace East
Suite 100
Englewood, CO 80112
(303) 790-1747

Center for Hazardous Materials Research
Stephen W. Paff
320 William Pitt Way
Pittsburgh, PA 15238
(412) 426-5320

COGNIS
Bill Fristad
2330 Circadian Way
Santa Rosa, CA 95407
(707) 575-7155

DAVY Research & Development, Ltd.
Dr. Graham Wightman
P.O. Box 37, Bowesfield Lane
Stockton-on-Tees
TS18 3HA England
44-642-607-108

Earth Decontaminators, Inc.
Steve Sawdon
2803 Barranca Pkwy.
Irvine, CA 92714
(714) 262-2290

Earth Treatment Technologies, Inc.
Troy DuGuay
Dutton Mill Industrial Park
396 Turner Way
Aston, PA 19014
(610) 497-6729

EET Corporation
Robert D. Peterson
11217 Outlet Dr.
Knoxville, TN 37932
(615) 671-7800

Electrokinetics, Inc.
Robert Marks/Yalcin Acar/Robert Gale
LA Business and Technology Center
South Stadium Drive, Suite 155
Baton Rouge, LA 70803-6100
(504) 388-3992

Electro-Pyrolsis, Inc.
Dr. J. Kenneth Wittle
996 Old Eagle School Rd.
Suite 118
Wayne, PA 19087
(610) 687-9070

EPS Environmental, Inc.
Noel Spindler
520 Victor Street
Saddle Brook, NJ 07662
(201) 368-7902

ETUS, Inc.
Mark Wemhoff
1511 Kastner Place
Sanford, FL 32771
(407) 321-7910

GAIA Services, Inc.
T.J. Lowrance
Loop Sta., P.O. Box 314
Chicago, IL 60690
(312) 329-0368

Geochem
Dr. Roman Z. Pyrih
12596 W. Bayaud Ave., Suite 205
Lakewood, CO 80228
(303) 988-8902

Geosafe Corp.
James E. Hansen
2950 George Washington Way
Richland, WA 99352
(509) 375-0710

Hazen Research, Inc.
Barry J. Jansen
4601 Indiana Street
Golden, CO 80403
(303) 279-4501

Horsehead Resource Development Co.
Regis J. Zagrocki
300 Frankfort Rd.
Monaca, PA 15061
(412) 773-2289

Integrated Chemistries, Inc.
Cathy Iverson
1970 Oakcrest Ave.
Suite 215
St. Paul, MN 55113
(612) 636-2380

IT Corporation
Edward Alperin
304 Directors Drive
Knoxville, TN 37933
(615) 690-3211

Microfluidics Corp.
Irwin Gruverman
90 Oak Street
Newton, MA 02164-9101
(617) 969-5452

NUKEM
John R. Weber
3000 Richmond Ave.
Houston, TX 77098
(713) 520-9494

On-Site Technologies
Benjamin Roberts, Ph.D.
1715 South Bascom Ave.
Campbell, CA 95008
(408) 371-4810

Onsite * Offsite Inc./Battelle PNL
Norman Banns
2042 Central Ave
Duarte, CA 91010
(818) 303-2229

Pittsburgh Mineral & Environmental Tech.
William F. Sutton
700 Fifth Avenue
New Brighton, PA 15066
(412) 843-5000

Portec, Inc.
Mark Mulloy
904 West 23rd Street
P.O. Box 220
Yankton, SD 57078-0220
(605) 665-8770

Recra Environmental, Inc.
James F. LaDue
10 Hazelwood Drive, Suite 110
Amherst, NY 14228-2298
(716) 691-2600

ReTech
Ronald K. Womack
100 Henry Station Road
P.O. Box 997
Ukiah, CA 95482
(707) 462-6522

Scientific Ecology
Patrick Keegan/David Grant
Nuclear Waste Technology Dept.
1501 Ardmore Blvd.
Pittsburgh, PA 15221
(412) 247-6255

S.G. Frantz Co., Inc.
Thomas D. Wellington
31 East Darrah Lane
Lawrence Township, NJ 08648
(609) 882-7100

Tuboscope Vetco
Dr. Myron I. Kuhlman
2835 Holmes Rd.
Houston, TX 77051
(713) 799-5289

Viking Industries
Don T. Pearson
1015 Old Lascassas Rd.
Murfreesboro, TN 37130
(615) 890-1018

Vortec Corporation
James G. Hnat
3370 Ridge Pike
Collegeville, PA 19426-3158
(610) 489-2255

APPENDIX D

SELECTED METAL-CONTAMINATED SITES

This appendix summarizes contaminant type, waste matrix, cleanup goals, remedial options, and status at selected sites where metals are key contaminants of concern. The sites were selected based on examination of Record of Decision (ROD), remedial investigation/feasibility study (RI/FS), Remedial Design/Remedial Action (RD/RA), and RCRA corrective action information for metal-contaminated sites, with emphasis on those having arsenic, cadmium, chromium, lead, or mercury contamination. These data are compiled to indicate the range of conditions and types of remedial options selected for metal-contaminated sites. The compilation is neither complete nor representative of all sites where metals are the prime contaminants of concern. The selection of sites generally avoids lead-acid battery recycling sites, wood preserving sites, pesticide sites, and mining and primary mineral sites because these sites are covered by other technical resources documents. However, sites that have recently issued RODs selecting innovative technologies are included. The sites cover the range of commercial and innovative technologies for metals remediation with an emphasis on innovative technologies.

TABLE D-1. SUMMARY OF SELECTED METAL-CONTAMINATED SITES

Region	Site Name/ Location/Site Type	Contaminants and Initial Conc. Range	Matrix	Cleanup Goal	Technology	Status	Source
1	Saco Tannery Waste Pits (OU-1 Final) Saco, Maine Leather tannery process wastes disposed to two 2-acre lagoons and 53 smaller disposal pits	Cr(III) (soil) 57,000 mg/kg Cr(III) (sediment) 50,000 mg/kg Cr(VI) (soil) 2,625 mg/kg Cr(VI) (sediment) 2,297 mg/kg As (soil) 33 mg/kg As (sediment) 1,210 mg/kg As (GW) 79 µg/L	Soil, sediment, sludge, GW, and SW	Total Cr, 2,000 mg/kg based on ecological risk assessment Pb, 125 mg/Kg As 60 mg/kg	Contingent upon the state designating the site a permanent conservation area: Groundwater pump and treatment, revegetation, wetland compensation, institutional controls	ROD date 09/27/89 Construction complete(a) 10/26/93	EPA/625/6-89/022 ROD Annual Report EPA 9355.6-05 Annotated Technical Reference
2	De Rewal Chemical (OU-1) Frenchtown, New Jersey Chemical company manufacturing textile preservative and fungicide	Cr (soil) <1,270 mg/kg Cu (soil) <4,160 mg/kg Hg (soil) <2.5 mg/kg Cyanide (soil) <304 mg/kg organics	Soil 8,000 yd^3	Cr (soil) 100 mg/kg Cr (GW) 50 µg/L Cu 170 mg/kg Hg 1 mg/kg Cyanide 12 mg/kg	Excavation and onsite incineration of organics Solidification of metal-contaminated soils and ash from incineration GW pumping and offsite treatment at a wastewater treatment plant Land use restrictions	ROD date 09/29/89	Annotated Technical Reference ROD Annual Report EPA 9355.6-05

(a) "Construction complete" indicates sites where all construction of cleanup remedies is complete but the site cannot yet be deleted from the NPL because long-term efforts such as groundwater cleanup may be required.

TABLE D-1. (continued)

Region	Site Name/ Location/Site Type	Contaminants and Initial Conc. Range	Matrix	Cleanup Goal	Technology	Status	Source
2	Ewan Property (OU-2 Final) Shamong Township, New Jersey 43-acre industrial waste disposal area	Cr 8 - 208 mg/L Pb 3 - 292 mg/L Cu 4.5 - 4,920 mg/L Pb 2 - 56,600 mg/kg Organics	Soil and GW 34,000 yd^3 22,000 yd^3 (soil)	Cr (GW) 50 μg/L Pb (GW) 50 μg/L Treated soil to meet State Solid Waste Regulations Treated water to meet state water quality criteria and MCLs	Excavating and treating soil with solvent extraction and soil washing followed by redepositing treated soil on site as clean fill Treating and disposing of spent solvent off site Treating spent washwater on site using GW treatment system Regrading and revegetation GW pumping and treatment followed by reinjection into the aquifer *Environmental monitoring*	ROD date 09/29/89 Currently preparing to perform drum removal and GW pump and treat Metals soil washing demo on hold Predesign completion planned 1995	ROD Annual Report EPA 9355.6-05
2	GE Wiring Devices (OU-1 Final) Puerto Rico 5-acre site for assembly of mercury switches	Hg (soil) ND to 62 mg/kg Hg (GW) ND to 7,000 μg/L	Soil, debris, and GW 1,500 yd^3 (soil) 500,000 gal (GW)	Hg 16.4 mg/kg or 21 ppb according to air monitoring (soil, GW, wastefill)	Onsite hydrometallurgical treatment of the soil, perched GW, and residues with treated material disposed of in former waste-fill area followed by cover with a clean soil Onsite treatment of leaching agent with residual discharge to POTW GW monitoring	ROD date 09/30/88 In design Completion planned 1993	Innovative Treatment Technologies Annual Status Report EPA/542-R-93-003 Annotated Technical Reference ROD Annual Report EPA 9355.6-05
2	Genzale Plating Co. Franklin Square, New York 0.5-acre electroplating site	Ba 36,400 mg/kg Cr 37,300 mg/kg Ni 58,000 mg/kg TCE 53 mg/kg	Soil and groundwater 2,080 yd^3 (soil and leach pit material)	Ba 3,500 mg/kg Cr 6.7 mg/kg Ni 30 mg/kg TCE 1 mg/kg	In situ vacuum extraction to remove organics, excavation, and offsite treatment and disposal, backfill with clean offsite soil Pumping and treatment of GW on site using precipitation and air stripping, GW reinjection, residuals treated off site	ROD date 03/29/91 Construction scheduled to begin late 1993	93/94 Guide to Superfund Sites, Pasha Publications, Inc., 1993

TABLE D-1. (continued)

Region	Site Name/ Location/Site Type	Contaminants and Initial Conc. Range	Matrix	Cleanup Goal	Technology	Status	Source
2	King of Prussia (OU-1) Winslow Township, New Jersey 10-acre abandoned waste disposal/ recycling facility	Cr (soil, sludge, and sediment 0 to 2 ft) <8,010 mg/kg	Soil, sediment, debris, and GW	Cr (soil) 483 mg/kg	Excavating lagoon sludge, soil adjacent to the lagoons, and sediment in the swale; treating these materials by soil washing for metals removal (using both physical separation and polishing with surfactants); and redepositing the residual materials in their original location on site	ROD date 09/28/90 Design completed ART performed full-scale soil washing from June to October 1993. 19,200 tons of soils were remediated. Approximately 85% of the soils were redeposited to their original location.	ROD Annual Report EPA 9355.6-05 Alternative Remedial Technologies (ART), Inc. News Release
		Cr (soil, sludge, and sediment 2 to 10 ft) <11,300 mg/kg					
		Cr (GW) <1,040 µg/L		Cr (GW) 50 µg/L			
		Cu (soil, sludge, and sediment 0 to 2 ft) <9,070 mg/kg		Cu (soil) 3,571 mg/kg	Excavating and disposing of buried drums, their contents, and visibly contaminated soil on site		
		Cu (soil, sludge, and sediment 2 to 10 ft) <16,300 mg/kg					
		Cu (GW) <12,500 µg/L		Cu (GW) 1,000 µg/L	Removing deteriorating tank trucks containing waste materials for offsite disposal		
		Pb (soil, sludge, and sediment 0 to 2 ft) <87 mg/kg		Pb (soil) 250 -1000 mg/kg target 500 mg/kg	GW pumping, treatment by air stripping, followed by reinjecting of GW and offsite disposal of residuals		
		Pb (soil, sludge, and sediment 2 to 10 ft) <389 mg/kg					
		Pb (GW) No data			Environmental monitoring Institutional controls including GW use restrictions		
		Hg (soil, sludge, and sediment 0 to 2 ft) <100 mg/kg		Hg (soil) 1 mg/kg			
		Hg (soil, sludge, and sediment 2 to 10 ft) <1.7 mg/kg					
		Hg (GW) Not detected		Hg (GW) 2 µg/L			

TABLE D-1. (continued)

Region	Site Name/ Location/Site Type	Contaminants and Initial Conc. Range	Matrix	Cleanup Goal	Technology	Status	Source
2	King of Prussia (continued)	Ni (soil, sludge, and sediment 0 to 2 ft) <387 mg/kg Ni (soil, sludge, and sediment 2 to 10 ft) <11,100 mg/kg Ni (GW) <4,670 µg/L		Ni (soil) 1,935 mg/kg Ni (GW) 210 µg/L			
2	Marathon Battery Company (OU-3 Final) Cold Spring, New York Nickel cadmium battery maker	Cd 0.3-3,000 mg/kg Ni 16-1,260 mg/kg VOCs including PCE and TCE	Sediment 30,083 yd^3 6,100 yd^3 (soil) 5,000 yd^3 (sediment)	Cd 10 mg/kg Ni No ARARs for sediments	Dredge sediments to a depth of 1 foot, followed by onsite chemical fixation, and offsite disposal at a sanitary landfill Sediment monitoring	ROD date 09/29/89 Operational Completion planned fall 1995	Annotated Technical Reference ROD Annual Report EPA 9355.6-05 93/94 Guide to Superfund Sites, Pasha Publications, Inc., 1993
2	Nascolite (OU-2 Final) Millville, Cumberland County, New Jersey 17.5-acre former plexiglas making facility	Pb (Soil) <41,800 mg/kg	Soil 8,000 yd^3	All unsaturated soil containing more than 500 mg/kg Pb will be excavated and stabilized on site	Excavating, treating, and stabilizing unsaturated and wetlands soil containing lead above 500 mg/kg; backfilling excavation pits using treated soil; transporting wetland sediment not suitable for stabilization to an offsite facility; restoring any affected wetlands Conducting asbestos abatement and offsite disposal Demolishing site structures in accordance with asbestos regulations; decontamination, onsite treatment, recycling, or offsite disposal of associated debris Institutional controls	ROD date 06/28/91 Construction planned 1994	ROD Annual Report EPA 9355.6-05 93/94 Guide to Superfund Sites, Pasha Publications, Inc., 1993

TABLE D-1. (continued)

Region	Site Name/ Location/Site Type	Contaminants and Initial Conc. Range	Matrix	Cleanup Goal	Technology	Status	Source
2	Preferred Plating Corp (OU-1) Farmingdale, New York 0.5-acre plating facility	Cr 56.3 - 5,850 mg/L Pb 4.6 - 437 mg/L Cd 8.4 - 399 mg/L organics	GW	GW cleanup goals based on SDWA, MCLs, and State water quality regulations	GW pumping and treatment using precipitation, carbon adsorption, and ion exchange; GW reinjection; offsite disposal of treatment residues	ROD date 09/22/89 To start 9/93 To complete summer 94	ROD Annual Report EPA 9355.6-05 Superfund Week 7(33):6 93/94 Guide to Superfund Sites, Pasha Publications, Inc., 1993
2	Ringwood Mines Landfill (OU-1 Final) New Jersey Paint sludge disposal	Pb (soil) <1,300 mg/kg Pb (GW) 85 ppb As (GW) 57 ppb Petroleum hydrocarbons	Soil	Pb (soil) 250 mg/kg Pb (GW) 50 ppb As (GW) 50 ppb	Soil sampling and excavation if needed, with offsite disposal, backfilling, regrading, and revegetation Groundwater and surface water monitoring	ROD date 09/29/88 Construction complete(a) 10/26/93 Scheduled to delete from NPL in 1996	Annotated Technical Reference 93/94 Guide to Superfund Sites, Pasha Publications, Inc., 1993
2	Roebling Steel (OU-2) Roebling, New Jersey 34-acre slag area	As 1.4 - 64.3 mg/kg Cd 0.84 - 9.7 mg/kg Cr 94.8 - 2,210 mg/kg Hg 0.09 - 458 mg/kg Pb 10.3 - 10,400 mg/kg	Soil and slag		Solidification of highly contaminated slag material. Grading and capping the entire slag area with a single layer soil cover and vegetation. Excavation of 160 yd^3 of contaminated soil and disposal at an appropriate off-site facility.	ROD date 9/26/91	93/94 Guide to Superfund Sites

TABLE D-1. (continued)

Region	Site Name/ Location/Site Type	Contaminants and Initial Conc. Range	Matrix	Cleanup Goal	Technology	Status	Source
2	Waldick Aerospace (OU-1) Wall Township, New Jersey 2-acre aerospace parts manufacturing facility	Cd (soil) <16,200 mg/kg Cr (soil) <4,390 mg/kg Zn (soil) <3,840 mg/kg Ni (soil) <140 mg/kg organics	Soil	Cd (soil) 3.0 mg/kg Cr (soil) 100 mg/kg Zn (soil) 350 mg/kg Ni (soil) 100 mg/kg	Air stripping of saturated zone (8,000 yd^3) Excavation and offsite disposal of 2,500 yd^3 of residuals Demolition or decontamination of a building selected depending on the volume of contaminated soil below the building Institutional controls	ROD date 09/29/87	Annotated Technical Reference ROD Annual Report EPA 9355.6-05
3	Aladdin Plating (OU-1) Clarks Summit, Pennsylvania 2-acre electroplating facility	Cr (soil) 1,000 mg/kg	Soil 12,000 yd^3	Cr (soil) 50 mg/kg	Excavation and offsite stabilization, followed by offsite disposal in a landfill, and replacement by clean fill	ROD date 09/27/88 Remedial action (S/S) completed	Annotated Technical Reference ROD Annual Report EPA 9355.6-05 93/94 Guide to Superfund Sites, Pasha Publications, Inc., 1993
3	Brown's Battery Breaking Site (OU-2) Pennsylvania Lead acid battery breaking	Pb No data Sulfates Acids Organics	Soil, GW, and battery casings	Pb No data	Treatment of casings and soil off site by innovative high-temperature lead recovery Pumping of GW with on-site treatment and disposal	ROD date 07/02/92 Predesign completion planned late 1993	Innovative Treatment Technologies Annual Status Report EPA/542-R-93-003 93/94 Guide to Superfund Sites, Pasha Publications, Inc., 1993

TABLE D-1. (continued)

Region	Site Name/ Location/Site Type	Contaminants and Initial Conc. Range	Matrix	Cleanup Goal	Technology	Status	Source
3	Eastern Diversified Metals (OU-3) Pennsylvania Metals reclamation for wire and cable Lead as additive in electrical insulation - chemical form lead phthalate in plastic chips	Pb (fluff) 1,490 mg/kg - >40,000 mg/kg	Waste insulation from wire (fluff) consisting primarily of polyvinyl chloride and polyethylene chips (~60%), fibrous material, paper, soil, and metal 6,140 yd^3 (fluff, soil)	Removal and recycling	Recycling of the fluff at an offsite facility by direct formation into products such as flooring, plastic lumber, or bumpers or recycling off site by separation and processing to produce usable plastic chip product Residuals not suitable for recycling will be tested for RCRA waste characteristics. Nonhazardous residuals will be disposed of to an offsite landfill. Hazardous residuals will be treated to remove the hazardous characteristic and disposed of to an offsite landfill Exposed soils will be sampled and analyzed Erosion and sedimentation controls will be implemented	ROD date 07/02/92	ROD Annual Report, EPA 9355.6-05 93/94 Guide to Superfund Sites, Pasha Publications, Inc. 1993
3	Halby Chemical (OU-1) New Castle, Delaware Production of sulfur compounds and chemical storage	As No data organics	Soil and debris in process plant area 10,300 yd^3 (soil)	Background levels established by sampling and analysis As about 10 mg/kg	Consolidate all debris on site into one area with possible offsite disposal Perform treatability study to determine proper S/S formulation, excavate the top 6 inches of surface soil, treat excavated soil by S/S, return treated soil to the excavation, cover with asphalt cap Long-term soil monitoring Deed restrictions	ROD date 06/28/91 In design	ROD Database 93/94 Guide to Superfund Sites, Pasha Publications, Inc., 1993

TABLE D-1. (continued)

Region	Site Name/ Location/Site Type	Contaminants and Initial Conc. Range	Matrix	Cleanup Goal	Technology	Status	Source
3	Palmerton Zinc (OU-1) Pennsylvania Defoliated mountainside due to zinc smelting	Cd (soil) 1,300 mg/kg Pb (soil) 6,475 mg/kg Zn (soil) 35,000 mg/kg	Soil around zinc smelter 27,500,000 tons	Cd 3 lb/acre Pb 100 lb/acre Zn 200 lb/acre Cr 100 lb/acre Hg 3 lb/acre	Onsite installation of concrete pad with berms to mix offsite sewage sludge and fly ash; application of lime and potash on target areas; application of fly ash and offsite sludge on target areas; application of grass seed, seedlings, and mulch Interim remedy Limited excavations in high-risk areas planned 4/93	ROD date 09/14/87 Stabilization in progress Construction expected to be completed in 1999	Annotated Technical Reference ROD Annual Report EPA 9355.6-05 93/94 Guide to Superfund Sites, Pasha Publications, Inc., 1993 <u>Superfund Week</u> 7(13):4
3	Palmerton Zinc (OU-2) Pennsylvania Zinc smelting	Cd (slag) 420 mg/L Cd (GW) 24 µg/L Zn (slag) 42,000 mg/L Zn (GW) 3,200 µg/L	Slag from zinc smelting, sediment, GW	Not applicable	Slope modification, non-RCRA Subtitle C cap, and revegetation Surface water diversion and treatment with lime-activated filtration lagoons and/or construction of wetlands Inspection, monitoring, and maintenance Wetlands restoration if needed	ROD date 06/29/88	Annotated Technical Reference ROD Annual Report EPA 9355.6-05
3	Saltville Waste Disposal Ponds (OU-1) Virginia Chloralkali plant	Hg 10 to 120 µg/L	Waste ponds	Hg (water) 0.05 µg/L	Upgrade run-on control Treat pond outfall with sulfide precipitation or carbon adsorption Institutional controls Interim remedy	ROD date 06/30/87 Construction completed	Annotated Technical Reference ROD Annual Report EPA 9355.6-05 93/94 Guide to Superfund Sites, Pasha Publications, Inc., 1993

TABLE D-1. (continued)

Region	Site Name/ Location/Site Type	Contaminants and Initial Conc. Range	Matrix	Cleanup Goal	Technology	Status	Source
3	Tonolli Corporation Nesquehoning, Pennsylvania Battery recycling	Pb 8,300 mg/kg As 61 mg/kg Cd 10.6 mg/kg	Soil, sludge, GW, SW	Pb 500 mg/kg, near residential area Pb 1,000 mg/kg in non-residential area	Offsite recycling of battery scrap Excavation and consolidation of soil, S/S treatment for soil with Pb > 1,000 mg/kg, onsite landfill disposal In situ groundwater treatment – construct limestone barrier and inject pH-adjusted water to enhance groundwater flow to barrier Decontaminate onsite building	ROD date 09/30/92 In predesign 1993 Federal approval but State has not yet accepted remedial alternative	93/94 Guide to Superfund Sites, Pasha Publications, Inc., 1993
3	Whitmoyer Laboratories (OU-1 Interim) Pennsylvania Laboratory facility	As <30,000 mg/kg organics 69,000 gallons of concentrated liquid waste	Liquid chemicals, tanks, and vessels	Removal	Consolidating waste liquids into three categories, transporting wastes off site for treatment, disposing treated liquids into offsite surface water, and disposing of solid residuals in an offsite landfill. Organic compounds in the liquids will be destroyed by thermal treatment or biodegradation, or will be recycled. Decontamination tanks and vessels will be left on site.	ROD date 06/30/89 Remedial action completed	ROD Annual Report EPA 9355.6-05 93/94 Guide to Superfund Sites, Pasha Publications, Inc., 1993

TABLE D-1. (continued)

Region	Site Name/ Location/Site Type	Contaminants and Initial Conc. Range	Matrix	Cleanup Goal	Technology	Status	Source
3	Whitmoyer Laboratories (OU-3 Final) Pennsylvania Laboratory facility	As 21 - 10,000 mg/kg	Soil, sediment, debris, and GW	Target cleanup goal As (surface soil) 21 mg/kg Action levels As (unsaturated soil) 450 mg/kg As (saturated soil) 210 μg/kg As (principal threat) 1,000 mg/kg As (GW) 50 μg/L	Excavation and fixation of soil/sediment using an iron-based or other fixation process Biological treatment of organics prior to or after fixation Offsite disposal Excavating and consolidating in the vadose zone lightly contaminated soil or sediment followed by capaping Capping any remaining surface soils with arsenic levels over 21 mg/kg anad other areas as needed Grading and revegetation Demolish surface structures GW pump and treat followed by on-site discharge, reinjection into the aquifer, or both Monitoring Institutional controls	ROD date 12/31/90 Design schedule to be completed Spring of 1995	ROD Annual Report EPA 9355.6-05 93/94 Guide to Superfund Sites, Pasha Publications, Inc., 1993

TABLE D-1. (continued)

Region	Site Name/ Location/Site Type	Contaminants and Initial Conc. Range	Matrix	Cleanup Goal	Technology	Status	Source
4	Bypass 601 (OU-1) North Carolina 2-acre battery recycling facility	Pb (surface soil) 18 - 110,000 mg/kg Pb (subsurface soil) 2.8 - 136,000 mg/kg Pb (GW) 5 - 2,300 μg/L SO_4 (surface soil) 46 - 10,800 mg/kg SO_4 (GW) 24.4 - 21,000 μg/L Cr (GW) 15 - 1,000 μg/L Organics	Soil and debris 57,000 yd^3 (soil)	Remedial objectives for soil excavation Pb (soil) 500 mg/kg Pb (sediment) 35 mg/kg Sb 24 mg/kg (residential risk scenario) 820 mg/kg (industrial risk scenario) Cr 56 mg/kg Mn 4,200 mg/kg S/S treated material to pass TCLP leach test	Demolish onsite buildings Excavate and consolidate contaminated surface soils; treat by S/S on site; onsite disposal of solidified materials; fill, regrade, and revegetate excavated area	ROD date 08/31/90 amended 04/20/93	ROD Annual Report EPA 9355.6-05

TABLE D-1. (continued)

Region	Site Name/ Location/Site Type	Contaminants and Initial Conc. Range	Matrix	Cleanup Goal	Technology	Status	Source
4	Bypass 601 (OU-2) North Carolina Industrial area adjacent to a battery recycling facility	Pb (soil) 96 - 62,250 mg/kg Sb (soil) 21 - 140 mg/kg Cr (soil) 6.5 - 52 mg/kg Mn (soil) 481 - 3,100 mg/kg	Soil and debris	Pb (soil) 500 mg/kg Pb (sediment) 35 mg/kg Pb (GW) 15 µg/L Sb 24 mg/kg (residential risk scenario) 820 mg/kg (industrial risk scenario) Cr (soil) 56 mg/kg Cr (GW) 50 µg/L Mn (soil) 4,200 mg/kg Mn (GW) 1,900 µg/L Soil excavated to levels stated above and S/S treated to pass TCLP leach test	Demolish onsite buildings Excavate and consolidate contaminated surface soils; treat by S/S on site; onsite disposal of solidified materials; fill, regrade, and revegetate excavated area Institutional and access controls Pump and treat GW on site by precipitation and air stripping and discharge treated GW to the POTW Continued GW monitoring	ROD date 04/20/93	ROD Annual Report EPA 9355.6-05

TABLE D-1. *(continued)*

Region	Site Name/ Location/Site Type	Contaminants and Initial Conc. Range	Matrix	Cleanup Goal	Technology	Status	Source
4	Flowood (OU-1 Final) Mississippi Ceramic manufacture	Pb (surface soil) 3 to 30 mg/kg with hot spots to 4,000 mg/kg Pb (subsurface soil) 2.7 to 12 mg/kg with hot spots to 3,620 mg/kg Pb (sediments) 4.5 to 141,000 mg/kg Pb (GW) 0.016 - 11.0 mg/L Pb (SW) 0.007 - 3.0 mg/L	Soil and sediment 6,000 yd^3	Pb (soil and sediment) 500 mg/kg	Excavation and S/S of contaminated soil and sediments followed by backfilling and capping with clean fill, as necessary (ATR) GW monitoring (ATR)	ROD date 09/30/88 Construction complete(a) 10/26/93	Annotated Technical Reference ROD Annual Report EPA 9355.6-05

TABLE D-1. (continued)

Region	Site Name/ Location/Site Type	Contaminants and Initial Conc. Range	Matrix	Cleanup Goal	Technology	Status	Source
4	Independent Nail (OU-1) Beaufort, South Carolina 24.6-acre electroplating facility	Cd (soil) 15 mg/kg Cd (sediment) 65 mg/kg Cr (soil) 130 mg/kg Cr (sediment) 2,000 mg/kg Ni (soil) 30 mg/kg Ni (sediment) 1,800 mg/kg Zn (soil) 230 mg/kg Zn (sediment) 15,000 mg/kg cyanide (soil) 0.8 mg/kg cyanide (sediment) 77 mg/kg	Soil and sediment	Cd (soil) 2.6 mg/kg Cr (soil) 5.3 mg/kg Ni (soil) 18.0 mg/kg Zn (soil) 1,785 mg/kg	Excavation of metal-contaminated soil and lagoon sediments, treatment with S/S, backfilling with a layer of clean soil, placement of treated soil about 2 feet above the high GW level, and soil covering	ROD date 09/28/87 Remedial action completed in 1988 (delisting in progress 1989)	EPA/625/6-89/022 Annotated Technical Reference ROD Annual Report EPA 9355.6-05 93/94 Guide to Superfund Sites, Pasha Publications, Inc., 1993

TABLE D-1. (continued)

Region	Site Name/ Location/Site Type	Contaminants and Initial Conc. Range	Matrix	Cleanup Goal	Technology	Status	Source
4	Palmetto Wood Preserving (OU-1) South Carolina Wood preserving treatment facility	Cr No data As No data	Soil and GW 19,895 yd^3 (soil) 10,500,000 gal (GW)	Soil cleanup will attain public health levels which include Cr 627 mg/kg and As 200 mg/kg. GW will attain MCL values which include Cr 50.0 µg/L, Cu 1,000 µg/L, and As 50.0 µg/L	Excavation of contaminated soil with onsite washing and backfilling of treated soil Pumping wastewater to onsite treatment facility GW pumping and treatment with offsite discharge to SW Installation of municipal water line or drilling new wells for affected residents	ROD date 09/30/87 Remedial action completed	ROD Annual Report EPA 9355.6-05 93/94 Guide to Superfund Sites, Pasha Publications, Inc., 1993
4	Pepper's Steel and Alloys (OU-1 Final) Medley, Florida 30-acre general industrial area	Pb (soil) 1,000 mg/kg As 1-200 mg/kg organics including PCB	Soil, sediment, GW 9,000 yd^3 (As) 21,500 yd^3 (Pb soil) amounts not additive	Pb (soil) 1,000 mg/kg As (soil) 5 mg/kg	Excavation, S/S, onsite disposal for soils Collection and offsite disposal for free oil Land use restrictions	ROD date 03/12/86 S/S completed	EPA/625/6-89/022 ROD Annual Report EPA 9355.6-05
5	Northernaire Plating (OU-1) Cadillac, Michigan Former electroplating facility	Cr 10 - 499 mg/kg Cd 10 - 460 mg/kg	GW, soil, and sewer sediment	Cr <50 mg/kg Cd <10 mg/kg	Excavation and offsite disposal of soil and sewer line to a privately owned RCRA facility Cleaning dust and hazardous residue from building floor, breaking up of floor and drywell, sampling of exposed soil, disposal of any contaminated debris and soil at a RCRA Subtitle C facility Backfilling of excavations with clean soil	ROD date 09/11/85 Remedial action completed	ROD Annual Report EPA 9355.6-05 93/94 Guide to Superfund Sites, Pasha Publications, Inc., 1993

TABLE D-1. (continued)

Region	Site Name/ Location/Site Type	Contaminants and Initial Conc. Range	Matrix	Cleanup Goal	Technology	Status	Source
5	Northernaire Plating (OU-2) Cadillac, Michigan Former electroplating facility	Cr No data organics	GW	Cr <50 μg/L GW will meet or exceed state and SDWA MCL standards.	Two-stage GW pumping and treatment using carbon adsorption to remove metals and air stripping with vapor-phase carbon adsorption to remove VOCs, treated water discharge to SW GW monitoring Access and land use restrictions	ROD date 09/29/89 In design	ROD Annual Report EPA 9355.6-05 93/94 Guide to Superfund Sites, Pasha Publications, Inc., 1993
5	MacGillis & Gibbs Co./Bell Lumber and Pole New Brighton, MN Wood treating facility	Cr 146 mg/kg As 221 mg/kg Cr 5,830 ug/L As 293 ug/L PAHs PCP	Soil, sediments, groundwater	No data obtained	SITE Demonstration of BioTrol, Inc. biological aqueous treatment system	Completed in 1989 AAR published EPA/540/A5-91/001	93/94 Guide to Superfund Sites, Pasha Publications, Inc., 1993 SITE Technology Profiles
5	Twin Cities Army Ammunition Plant, New Brighton, MN	Pb 86,000 ppm Hg 15 ppm Cr 350 ppm Cd 20 ppm	Soil 5,000 yd^3	Pb 300 ppm Hg 0.3 ppm Cr 100 ppm Cd 4 ppm	Soil washing/soil leaching	Scheduled to complete Summer 1994	Fact Sheet No. 94-14

TABLE D-1. (continued)

Region	Site Name/ Location/Site Type	Contaminants and Initial Conc. Range	Matrix	Cleanup Goal	Technology	Status	Source
5	Zanesville Well Field (OU-1 Final) Zanesville, Ohio	Pb No data As No data Cr No data Hg No data Inorganics VOCs	Soil and GW 37,800 yd^3 (soil)	Pb 12 mg/kg Chemical-specific soil cleanup goals based on risk-based levels for cumu-lative excess lifetime cancer risk $<10^{-6}$ and an HI <1 Chemical specific GW cleanup goals based on SDWA and MCL	In situ soil vapor extraction for about 36,000 yd^3 soil and source areas contaminated with VOCs Soil washing treatment for about 1,800 yd^3 of inorganic contaminated soil, treated soil replaced on site, concentrated waste and treatment residuals disposed of off site, with further treatment, if needed GW pumping and treatment by air stripping Site access restrictions	ROD date 09/30/91 Predesign to be completed late 1993	ROD Annual Report EPA 9355.6-05
6	Gurley Pit (OU-1) Edmondson, Arkansas Pits used for disposal of sludge from refining of used motor oil	Pb (sludge) 14,000 mg/kg Pb (oil) 80 mg/kg Ba (sludge) 936 mg/kg Zn (sludge) 1,530 mg/kg PCBs	Soil, sludge, sediments, oil, and water 432,470 ft^3 (soil, sludge, sediment) 4,100,000 gal (water)	No data obtained	Onsite water treatment to meet NPDES discharge criteria Stabilization of pit sludge, sediments, and contaminated soil followed by onsite disposal in a RCRA cell Incinerate oils in a PCB approved incinerator Limit site access	ROD date 10/06/86 (interim) Remedial action completed	Annotated Technical Reference 93/94 Guide to Superfund Sites, Pasha Publications, Inc., 1993

TABLE D-1. (continued)

Region	Site Name/ Location/Site Type	Contaminants and Initial Conc. Range	Matrix	Cleanup Goal	Technology	Status	Source
6	Odessa Chromium (OU-2) Odessa, Texas Groundwater probably contaminated by electroplating operations	Cr (GW) 5.5 mg/L	GW and debris	Cr (GW) <0.05 mg/L or the MCL promulgated prior to design	Extraction of GW from a perched water-bearing zone and the Trinity aquifer, treatment with electrochemical methods, reinjection of treated GW to the aquifer Demolition and disposal of building Site monitoring for at least 30 years	ROD date 03/18/88 Construction underway	ROD Annual Report EPA 9355.6-05 93/94 Guide to Superfund Sites, Pasha Publications, Inc., 1993
6	Pesses Chemical (OU-1 Final) Fort Worth, Texas Reclamation of nickel cadmium batteries and sludges	Cd (soil) <2,400 mg/kg Ni (soil) <3,200 mg/kg Pb No data	Soil, sludge, and debris 16.6 yd^3 (sludge)	Cd 15 mg/kg Ni 100 mg/kg	Consolidate offsite contaminated soils with onsite contaminated soils, treat soils by in situ S/S, concrete cap within fenced area, subtitle C clay cap (or equivalent) on south field Metal warehouse and equipment cleaned and left in place Site maintained and inspected every 5 years	ROD date 12/22/88 S/S of 12,500 cu.yd soil completed	Annotated Technical Reference ROD Annual Report EPA 9355.6-05 93/94 Guide to Superfund Sites, Pasha Publications, Inc., 1993
7	Shaw Avenue Dump Site (OU-1) Charles City, Iowa	As (up to 50,000 mg/kg), PAHs	Soil	As (soil) 50 ppm	Fixation/stabilization of chemical fill and contaminated soil. Installation of a low permeability cap to protect fixed/stabilized material. Groundwater monitoring	ROD date 9/27/91 S/S completed Feb. 1994	ROD Annual Report EPA 9355.6-05 93/94 Guide to Superfund Sites, Pasha Publications, Inc., 1993

TABLE D-1. (continued)

Region	Site Name/ Location/Site Type	Contaminants and Initial Conc. Range	Matrix	Cleanup Goal	Technology	Status	Source
7	Vogel Paint and Wax (OU-1 Final) Maurice, Iowa 2-acre paint waste disposal facility	Cd (soil) 0.2-6.4 mg/kg Cr(III) (soil) 4.9-21,000 mg/kg Cr(III) (GW) BDL-80 μg/L Cr(III) (SW) BDL-12 μg/L Pb (soil) 5.2-4,000 mg/kg Pb (GW) BDL-320 μg/L Pb (SW) BDL-26 μg/L As (soil) 4.8-65 mg/kg Hg (soil) BDL-65 mg/kg Hg (GW) BDL-110 mg/L Ni (soil) 10.3-25.9 mg/kg Zn (soil) 15.5-12,000 mg/kg Zn (GW) BDL-240 μg/L Zn (SW) 30-40 μg/L organics	Soil, GW, and SW 3,000 yd^3 (soil) Cr (GW) 0.10 mg/L Pb (GW) 0.005 mg/L	Soil treatment will achieve leaching standards	Biotreatment of low metal content soils in a fully contained surface unit Incineration of high metals soils Stabilization and onsite disposal of treated soils Offsite incineration and recycling of leachate and offsite treatment of excess leachate at POTW Pump and treat groundwater by air stripping followed by discharge Groundwater and air monitoring	ROD date 09/20/89 Construction underway	Annotated Technical Reference ROD Annual Report EPA 9355.6-05 93/94 Guide to Superfund Sites, Pasha Publications, Inc., 1993

TABLE D-1. (continued)

Region	Site Name/ Location/Site Type	Contaminants and Initial Conc. Range	Matrix	Cleanup Goal	Technology	Status	Source
7	E.I. DuPont De Nemours (OU-1) West Point, Iowa Paint waste disposal	As 2.7 - 23.40 mg/kg Cd 5.4 - 510 mg/kg Cr 15.10 - 1,830 mg/kg Pb 60 - 38,950 mg/kg organics	Soil and debris	As No data obtained Cd (soil) 20 µg/kg Cr (soil) No data Pb (soil) 350 µg/kg	S/S treatment of soil followed by covering the stabilized mass with clean soil and vegetation Removing and disposing off site any debris not amenable to S/S treatment at an authorized RCRA landfill GW monitoring Institutional controls	ROD date 05/28/91 Construction complete[a] 10/26/93	ROD Annual Report EPA 9355.6-05
7	Mid-America Tanning (OU-1) Sergeant Bluff, Iowa Leather tanning wastewater and debris discharge to surface soil or disposal trenches	Cr No data Pb No data	Soil, sludge, sediment, debris, and SW 8,300 yd^3 (soil) 44,500 yd^3 (sediment) 1,293 yd^3 (sludge)	Cr 2,490 mg/kg	In situ S/S of contaminated soil and impoundment sediment Immobilizing consolidated trench sludge on site followed by disposal off site or on site Removing and disposing of debris off site Discharging impoundment water on site through an NPDES-permitted outfall or treatment, if needed, with offsite discharge to a POTW Capping, grading, and seeding contaminated areas GW monitoring Institutional controls	ROD date 09/24/91 In design	ROD Annual Report EPA 9355.6-05 93/94 Guide to Superfund Sites, Pasha Publications, Inc., 1993

TABLE D-1. (continued)

Region	Site Name/ Location/Site Type	Contaminants and Initial Conc. Range	Matrix	Cleanup Goal	Technology	Status	Source
9	Beckman Instruments (OU-1 Final) Porterville, California Manufacture and repair of electronic instruments	Pb (soil) 1,280 mg/kg chlorinated orgnics (GW)	Soil and GW 740 yd^3 (soil)	Pb (soil) 200 mg/kg	Excavation and offsite disposal of lead-contaminated soil Groundwater pump and treat and discharge to infiltration basins or irrigation canals Groundwater monitoring	ROD date 09/26/89 Construction complete[a] 10/26/93	Annotated Technical Reference ROD Annual Report EPA 9355.6-05
9	Selma Treating Co. Selma, California Wood treatment facility	As 4,120 mg/kg Cr 3,910 mg/kg Cu 1,870 mg/kg Pentachlorphenol	GW and soil	As (soil) 50 mg/kg Cr (GW) 50 μg/kg	Excavation of soil, on-site treatment using S/S; on-site disposal, RCRA cap. GW pumping and treatment with precipitation, coagulation, and flocculation; reinjection into the aquifer or off-site discharge. SITE Demonstration of Silicate Technology Corporation Chemical Fixation/Solidification Treatment Technology	ROD date 09/24/88 SITE Demo AAR completed EPA/540/AR-92/010	93/94 Guide to Superfund Sites, Pasha Publications, Inc., 1993 SITE Technology Profiles
10	Alaskan Battery Enterprises Fairbanks, Alaska Battery recycling	Pb No data obtained	Soil	No data obtained	SITE Demonstration of Brice Environmental Services (BESCORP) USA soil washing technology	SITE Demo AAR in preparation Construction complete[a] 10/26/93	SITE Technology Summary

TABLE D-1. (continued)

Region	Site Name/ Location/Site Type	Contaminants and Initial Conc. Range	Matrix	Cleanup Goal	Technology	Status	Source
10	Frontier Hard Chrome (OU-1) Vancouver, Washington Chromium plating	Cr No data obtained	Soil and structures Soil 7,400 yd^3	Soil with chromium >550 mg/kg will be treated	Excavation of soil, onsite treatment using chemical stabilization, onsite disposal of treated materials Demolition of site buildings Placement of final cover	ROD date 12/30/87	ROD Annual Report EPA 9355.6-05 93/94 Guide to Superfund Sites, Pasha Publications, Inc., 1993
10	Frontier Hard Chrome (OU-2) Vancouver, Washington Chromium plating	Cr No data obtained organics	GW 45,000 ft^2 (plume area)	Cr <0.050 mg/L Remedy prevents public exposure to drinking water which exceeds MCLs Treated water must also meet NPDES and other applicable limits	GW pumping and treatment using selective media ion exchange to remove chromium followed by carbon adsorption to remove VOCs, treated water discharged to river or city sewer system Institutional controls on GW usage and new well drilling	ROD date 07/05/88	ROD Annual Report EPA 9355.6-05

TABLE D-1. (continued)

Region	Site Name/ Location/Site Type	Contaminants and Initial Conc. Range	Matrix	Cleanup Goal	Technology	Status	Source
10	Gould Site (OU-1) Portland, Oregon Lead smelter	Pb (soil) 14 - 19,000 mg/kg Pb (GW) <0.05 mg/L Pb (SW) <0.28 mg/L Pb (sediment) 16 - 12,000 mg/kg	Soil and sediment 80,800 yd^3 (battery casings) 3,370 yd^3 (surface soil) 13,650 yd^3 (subsurface soil) 5,500 yd^3 (sediment) 6,000 yd^3 (matte)	Pb (surface soil) 1000 mg/kg Pb (subsurface soil) EP Tox Pb (air) 1.5 $\mu g/m^3$	Excavation and separation of battery casings and matte, recycling of those components that can be recycled, offsite RCRA landfill disposal of hazardous nonrecyclable components; and onsite disposal of nonhazardous nonrecyclable components. Excavation, S/S treatment, and onsite disposal of contaminated soils, sediment Construction of soil cover and revegetation Decontamination of buildings and debris with offsite disposal of residues Drainage control Installation of new residential well Deed restrictions GW and SW monitoring	ROD date 03/31/88 Operational Completion planned 1995	ROD Annual Report EPA 9355.6-05 Annotated Technical Reference

TABLE D-1. (Continued)

Region	Site Name/ Location/Site Type	Contaminants and Initial Conc. Range	Matrix	Cleanup Goal	Technology	Status	Source
10	Martin Marietta (OU-1 Final) The Dalles, Oregon Aluminum manufacturing potliner and cathode wastes used as fill	As (soil) no data fluoride (soil) <2,880 mg/kg SO_4 (landfill leachate) <2,660 mg/L PAHs	Soil, GW, and debris 64,870 yd^3	As (soil) 65 mg/kg Fluoride (GW) 9.7 mg/L SO_4 (GW) 3,020 mg/L	Consolidation of cathode waste material into an existing landfill followed by capping Soil cover over scrubber/sludge ponds Plugging abandoning wells and connecting users to municipal water supply Collection and treatment of leachate and perched water by oxidation/ reduction with discharge to existing sewer ATR or onsite recycling pond ROD Summary Recover contaminated GW GW monitoring and institutional controls	ROD date 09/29/88 Operational	Annotated Technical Reference 93/94 Guide to Superfund Sites, Pasha Publications, Inc., 1993 ROD Annual Report EPA 9355.6-05
10	United Chrome Products (OU-1) Corvallis, Oregon Electroplating	Cr 142 - 689 mg/L	Soil and GW 350 tons (offsite disposal)	Cr (confined aquifer) 0.05 mg/L Cr (unconfined aquifer) 10 mg/L Cr (treated water discharge) 0.3 to 0.4 mg/L typical expected	In situ soil flushing in unsaturated zone Excavation and offsite disposal for soils in the saturated zone Groundwater pump and treat using chemical reduction and precipitation with discharge to POTW or SW	ROD date 09/12/86 Construction complete[a] 10/26/93 Operation started summer 1988 and will continue indefinitely	Innovative Treatment Technologies Annual Status Report EPA/542-R-93-003 ROD Annual Report EPA 9355.6-05

(a) "Construction complete" indicates sites where all construction of cleanup remedies is complete but the site cannot yet be deleted from the NPL because long-term efforts such as groundwater cleanup may be required.

APPENDIX E

SUMMARY OF BEST DEMONSTRATED AVAILABLE TECHNOLOGIES FOR METAL-CONTAMINATED WASTES

In the mid-1980s to early 1990, U.S. EPA collected and evaluated performance data to identify Best Demonstrated Available Technologies (BDATs) for treatment of RCRA wastes (McCoy and Associates, Inc., 1993). The EPA has proposed modifications to the hazardous waste recycling regulations to streamline regulatory decisions regarding certain types of recycling (58 *FR* 48092, September 14, 1993). These studies included critical analysis of treatability data for metal-contaminated wastes. The following subsections summarize conclusions about treatment options for metal-contaminated wastes. The regulatory basis for BDAT standards development requires application of proven, commercially available technology. These requirements focus the BDATs on conventional technology. The technologies provide a good starting basis for review of treatment of wastes at CERCLA sites. However, technology selection at CERCLA sites should be developed based on site-specific characteristics and risks and should consider innovative technologies. Space is not available to describe all of the material the U.S. EPA considered in developing the BDAT standards for metal wastes. This appendix contains tables showing the treatment standards and BDATs for RCRA waste codes having arsenic, cadmium, chromium, lead, or mercury as a constituent of concern. In addition to the final BDAT documents, references in this section contain detailed tabulations of treatability data for RCRA wastestreams. Typical types of BDATs for metal-contaminated waste are summarized in Table E-1. Examples of RCRA wastes that often can be found at Superfund sites are shown in Table E-2. BDATs for a variety of RCRA wastes are summarized in Table E-3.

TABLE E-1. SUMMARY OF BDATs FOR METAL-CONTAMINATED RCRA WASTES

	Example BDATs for Metal Wastes	
Metal Contaminant	Nonwastewater	Wastewater
Arsenic	Vitrification	Chemical precipitation
Cadmium	Stabilization or metal recovery	Chemical precipitation
Chromium	Chromium reduction and S/S	Chromium reduction and S/S
Mercury	Metal recovery (>260 mg/kg) or acid leaching followed by chemical precipitation	Chemical precipitation with sulfide
Lead	Stabilization or metal recovery	Chemical precipitation

TABLE E-2. LISTED HAZARDOUS WASTES FREQUENTLY FOUND AT METAL-CONTAMINATED SITES (FROM PART 251 SUBPART D, LISTS OF HAZARDOUS WASTES[a]

Section 261.31 Hazardous Wastes from Nonspecific Sources

F006	Wastewater treatment sludges from electroplating operation except from the following processes: (1) sulfuric acid anodizing of aluminum; (2) tin plating on carbon steel; (3) zinc plating (segregated basis) on carbon steel; (4) aluminum or zinc-aluminum plating on carbon steel; (5) cleaning/stripping associated with tin, zinc, and aluminum plating on carbon steel; and (6) chemical etching and milling of aluminum.

Section 261.32 Hazardous Wastes from Specific Sources

The following inorganic pigments are listed wastes because hexavalent chromium and/or lead are the hazardous constituents.

K002	Wastewater treatment sludge from the production of chrome yellow and orange pigments
K003	Wastewater treatment sludge from the production of molybdate orange pigments
K004	Wastewater treatment sludge from the production of zinc yellow pigments
K005	Wastewater treatment sludge from the production of chrome green pigments
K006	Wastewater treatment sludge from the production of chrome oxide green pigments (anhydrous and hydrated)
K007	Wastewater treatment sludge from the production of iron blue pigments
K008	Oven residue from the production of chrome oxide green pigments

The following wastes from petroleum and metals refining are listed wastes because hexavalent chromium, lead, and/or cadmium are the hazardous constituents.

K048	Dissolved air flotation (DAF) float from the petroleum refining industry
K049	Slop oil emulsion solids from the petroleum refining industry
K050	Heat exchanger bundle cleaning sludge from the petroleum refining industry
K051	API separator sludge from the petroleum refining industry
K052	Tank bottoms (leaded) from the petroleum refining industry
K061	Emission control dust/sludge from the primary production of steel in electric furnaces
K062	Spent pickle liquor generated by steel finishing operation of facilities within the iron and steel industry
K069	Emission control dust/sludge from secondary lead smelting
K100	Waste leaching solution from acid leaching of emissions control dust/sludge from secondary lead smelting
K086	Solvent washes and sludges, caustic washes and sludges, or water washes and sludges from cleaning tubs and equipment used in the formulation of ink from pigments, driers, soaps, and stabilizers containing chromium and lead

The following are listed wastes because arsenic is the hazardous constituent.

K084	Wastewater treatment sludges generated during the production of veterinary pharmaceuticals from arsenic or organoarsenic compounds
K101	Distillation tar residues from the distillation or aniline-based compounds in the production of veterinary pharmaceuticals from arsenic or organoarsenic compounds
K102	Residue from the use of activated carbon for decolorization in the production of veterinary pharmaceuticals from arsenic or organoarsenic compounds
K031	By-product salts generated in the production of MSMA and cacodylic acid

The following are listed wastes because mercury is the hazardous constituent.

K071	Brine purification muds from the mercury cell process in chlorine production, where separately prepurified brine is not used
K106	Wastewater treatment sludge from the mercury cell process in chlorine production

TABLE E-2. (continued)

The following are listed wastes because lead is the hazardous constituent	
K046	Wastewater treatment sludges from the manufacturing, formulation, and loading of lead-based initiating compounds
Section 261.33 Discarded Commercial Chemical Products, Off-Specification Species, Container Residues, and Spill Residues Thereof	
U15134	Mercury

(a) The listed hazardous wastes are included for reference purposes and to provide a familiarity with the type of wastes that are listed. Even if listed, certain wastes may be excluded from regulation (40 CFR 261.4).

Source: U.S. EPA, Annotated Technical Reference.

Different BDATs and treatment standards are usually assigned for nonwastewater and wastewater. Nonwastewater is the U.S. EPA designation for solid or high-solids-content materials such as soils, slags, sludges, slurries, or organic liquids. Wastewaters are low-solids-content aqueous wastes.

E.1 BEST DEMONSTRATED AVAILABLE TECHNOLOGIES FOR ARSENIC WASTES

The U.S. EPA established vitrification as the BDAT for the nonwastewater from a variety of arsenic-containing wastes including:

- K031 (by-product salts generated in the production of MSMA and cacodylic acid)
- K084 (wastewater treatment sludges generated during the making of veterinary pharmaceuticals from arsenic and organoarsenic compounds)
- K101 (distillation tar residues from the distillation of aniline-based compounds in the production of veterinary pharmaceuticals from arsenic and organoarsenic compounds)
- K102 (residue from the use of activated carbon for decolorization in the production of veterinary pharmaceuticals from arsenic and organoarsenic compounds)
- D004 (arsenic characteristic)
- Arsenic-containing P and U wastes

TABLE E-3. TABULATION OF BEST DEMONSTRATED AVAILABLE TECHNOLOGY STANDARDS FOR METAL-CONTAMINATED WASTE

Hazardous Waste Description/Code	Constituents of Concern (Remaining Constituents)	Concentration-Based Standard for Nonwastewater		Concentration-Based Standard for Wastewater		Treatment Method Specified for Technology-Based Standard
		TCLP (mg/L)	BDAT	Total Composition (mg/L)	BDAT	
D004 – Arsenic	Arsenic	5.0	Vitrification	5.0	Chemical precipitation	
D006 – Cadmium	Cadmium	1.0	Stabilization or metal recovery	1.0	Chemical precipitation	
D006 – Cadmium batteries subcategory		–	(Treatment method specified)	–	–	Thermal recovery of metal in an industrial furnace
D007 – Chromium	Chromium (total)	5.0	Chromium reduction, stabilization	5.0	Chromium reduction, precipitation	
D008 – Lead	Lead	5.0	Stabilization	5.0	Chemical precipitation, sludge dewatering	
D008 – Lead acid batteries(a)		–	(Treatment method specified)	–	–	Thermal recovery of lead
D009 – Mercury • High-mercury subcategory	Mercury	–	(Treatment method specified)	0.20	Chemical precipitation with sulfide	Thermal recovery(b)
• Low-mercury subcategory		0.20	Acid leaching followed by chemical precipitation, dewatering	0.20	Chemical precipitation with sulfide	
F006 – Wastewater treatment sludges from electroplating operations	Cadmium Chromium (total) Lead (Cyanides, other metals)	0.066 5.2 0.51	Chemical precipitation, settling, filtration, and stabilization (metals); alkaline chlorination (cyanides)	1.6 0.32 0.040	Chromium reduction, precipitation with lime and sulfides, sludge dewatering (metals); alkaline chlorination (cyanides)	
F007 – Spent cyanide plating bath solutions from electroplating operations	Cadmium Chromium (total) Lead (Cyanides, other metals)	0.066 5.2 0.51	Chemical precipitation, settling, filtration, and stabilization (metals); alkaline chlorination (cyanides)	– 0.32 0.04	Chemical precipitation, settling, sludge dewatering (metals); alkaline chlorination (cyanides)	

TABLE E-3. (continued)

Hazardous Waste Description/Code	Constituents of Concern (Remaining Constituents)	Concentration-Based Standard for Nonwastewater		Concentration-Based Standard for Wastewater		Treatment Method Specified for Technology-Based Standard
		TCLP (mg/L)	BDAT	Total Composition (mg/L)	BDAT	
F008 – Plating bath sludges from the bottom of plating baths from electroplating operations where cyanides are used in the process	Cadmium Chromium (total) Lead (Cyanides, other metals)	0.066 5.2 0.51	Chemical precipitation, settling, filtration, and stabilization (metals); alkaline chlorination (cyanides)	– 0.32 0.04	Chemical precipitation, setting, sludge, dewatering (metals); alkaline chlorination (cyanides)	
F009 – Spent stripping and cleaning bath solutions from electroplating operations where cyanides are used in the process	Cadmium Chromium (total) Lead (Cyanides, other metals)	0.066 5.2 0.51	Chemical precipitation, settling, filtration, and stabilization (metals); alkaline chlorination (cyanides)	– 0.32 0.04	Chemical precipitation, settling, sludge dewatering (metals); alkaline chlorination (cyanides)	
F011 – Spent cyanide solutions from salt bath pot cleaning from metal heat treating operations	Cadmium Chromium (total) Lead (Cyanides, other metals)	0.066 5.2 0.51	Chemical precipitation, settling, filtration, and stabilization (metals); electrolytic oxidation followed by alkaline chlorination (cyanides)	– 0.32 0.04	Chemical precipitation, settling, sludge dewatering (metals); alkaline chlorination (cyanides)	
F012 – Quenching wastewater treatment sludges from metal heat treating operations where cyanides are used in the process	Cadmium Chromium (total) Lead (Cyanides, other metals)	0.066 5.2 0.51	Chemical precipitation, settling, filtration, and stabilization (metals); electrolytic oxidation followed by alkaline chlorination (cyanides)	– 0.32 0.04	Chemical precipitation, settling, sludge dewatering (metals); alkaline chlorination (cyanides)	

TABLE E-3. (continued)

Hazardous Waste Description/Code	Constituents of Concern (Remaining Constituents)	Concentration-Based Standard for Nonwastewater		Concentration-Based Standard for Wastewater		Treatment Method Specified for Technology-Based Standard
		TCLP (mg/L)	BDAT	Total Composition (mg/L)	BDAT	
F019 – Wastewater treatment sludges from the chemical conversion coating of aluminum	Chromium (total) (Cyanides)	5.2	Stabilization (chromium); alkaline chlorination (cyanides)	0.32	Chromium reduction, chemical precipitation with lime and sulfides, sludge dewatering (metals); alkaline chlorination (cyanides)	
F024 – Wastes from the production of chlorinated aliphatic hydrocarbons	Chromium (total) Lead (Organics, nickel)	0.073 [Reserved]	Rotary kiln incineration; stabilization of incinerator ash (metals)	0.35 –	Incineration for organics (treatment method specified)	
F039 – Multisource leachate organics	Arsenic Cadmium Chromium (total) Lead Mercury (Organics, other metals)	5.0 0.066 5.2 0.51 0.025	Stabilization (metals); incineration (organics)	1.4 0.20 0.37 0.28 0.15	Biological treatment followed by chemical precipitation; or wet-air oxidation followed by carbon adsorption followed by chemical precipitation	
K001 – Bottom sediment sludge from the treatment of wastewaters from wood-preserving processes that use creosote and/or pentachlorophenol	Lead (Organics)	0.51	Rotary kiln incineration, followed by stabilization of the ash	0.037	Chemical precipitation	

TABLE E-3. (continued)

Hazardous Waste Description/Code	Constituents of Concern (Remaining Constituents)	Concentration-Based Standard for Nonwastewater		Concentration-Based Standard for Wastewater		Treatment Method Specified for Technology-Based Standard
		TCLP (mg/L)	BDAT	Total Composition (mg/L)	BDAT	
K002 – Wastewater treatment sludge from the production of chrome yellow and orange pigments	Chromium (total) Lead	0.094 0.37	Chemical precipitation, filtration, sludge dewatering (metals)	0.9 3.4	Chromium reduction, precipitation, sludge dewatering (metals)	
K003 – Wastewater treatment sludge from the production of molybdate orange pigments	Chromium (total) Lead	0.094 0.37	Chemical precipitation, filtration, sludge dewatering (metals)	0.9 3.4	Chromium reduction, precipitation, sludge dewatering (metals)	
K004 – Wastewater treatment sludge from the production of zinc yellow pigments	Chromium (total) Lead	0.094 0.37	Chemical precipitation, filtration, sludge dewatering (metals)	0.9 3.4	Chromium reduction, precipitation, sludge dewatering (metals)	
K005 – Wastewater treatment sludge from the production of chrome green pigments	Chromium (total) Lead (Cyanides)	0.094 0.37	Chemical precipitation, filtration, sludge dewatering (metals)	0.9 3.4	Chromium reduction, precipitation, sludge, dewatering (metals); alkaline chlorination (cyanides)	
K006 – Wastewater treatment sludge from the production of chrome oxide green pigments						
• Anhydrous	Chromium (total) Lead	0.094 0.37	Chemical precipitation, filtration; stabilization (chromium)	0.9 3.4	Chromium reduction, precipitation, sludge dewatering (metals)	
• Hydrated	Chromium (total) Lead	5.2 –	Chemical precipitation, filtration; stabilization (chromium)	0.9 3.4	Chromium reduction, precipitation, sludge dewatering (metals)	

TABLE E-3. (continued)

Hazardous Waste Description/Code	Constituents of Concern (Remaining Constituents)	Concentration-Based Standard for Nonwastewater		Concentration-Based Standard for Wastewater		Treatment Method Specified for Technology-Based Standard
		TCLP (mg/L)	BDAT	Total Composition (mg/L)	BDAT	
K007 – Wastewater treatment sludge from the production of iron blue pigments	Chromium (total) Lead (Cyanides)	0.094 0.37	Chemical precipitation, filtration; sludge dewatering (metals)	0.9 3.4	Chromium reduction, precipitation, sludge dewatering (metals); alkaline chlorination (cyanides)	
K008 – Oven residue from the production of chrome oxide green pigments	Chromium (total) Lead	0.094 0.37	Chemical precipitation, filtration, sludge dewatering (metals)	0.9 3.4	Chromium reduction, precipitation, sludge dewatering (metals)	
K015 – Still bottoms from the distillation of benzyl chloride	Chromium (total) (Organics, Nickel)	1.7	Stabilization (metals); incineration (organics)	0.32	Separate BDAT for wastewaters not specified	
K022 – Distillation bottom tars from the production of phenol/acetone from cumene	Chromium (total) (Organics, Nickel)	5.2	Incineration or fuel substitution, solidification of ash	0.35	Biological treatment, steam stripping, carbon adsorption, or liquid extraction (organics); chemical precipitation (metals)	
K028 – Spent catalyst from the hydrochlorinator reactor in production of 1,1,1-trichloroethane	Cadmium Chromium (total) Lead (Organics, Nickel)	– 0.073 0.021	Stabilization (metals); rotary kiln incineration (organics)	6.4 0.35 0.037	Sulfide precipitation followed by settling, filtration, and dewatering for metals removal	
K031 – By-product salts generated in producing MSMA and cacodylic acid	Arsenic	5.6	Vitrification	0.79	Chemical precipitation	

TABLE E-3. (continued)

Hazardous Waste Description/Code	Constituents of Concern (Remaining Constituents)	Concentration-Based Standard for Nonwastewater		Concentration-Based Standard for Wastewater		Treatment Method Specified for Technology-Based Standard
		TCLP (mg/L)	BDAT	Total Composition (mg/L)	BDAT	
K046 – Wastewater treatment sludges from the manufacturing, formulation, and loading of lead-based initiating compounds	Lead	0.18	Deactivation, if reactive, followed by stabilization	0.037	Alkaline precipitation, settling, and filtration	
K048 – Dissolved air flotation float from the petroleum refining industry	Chromium (total) Lead (Organics, Nickel)	1.7 –	Solvent extraction or incineration (organics); stabilization of ash	0.20 0.037	Chromium reduction, chemical precipitation, vacuum filtration (metals); incineration (cyanides)	
K049 – Slop oil emulsion solids from the petroleum refining industry	Chromium (total) Lead (Organics, Nickel)	1.7 –	Solvent extraction or incineration (organics); stabilization of ash	0.20 0.037	Chromium reduction, chemical precipitation, vacuum filtration (metals); incineration (cyanides)	
K050 – Heat exchanger bundle cleaning sludge from petroleum refining industry	Chromium (total) Lead (Organics, Nickel, Cyanides)	1.7 –	Solvent extraction or incineration (organics); stabilization of ash	0.20 0.037	Chromium reduction, chemical precipitation, vacuum filtration (metals); incineration (cyanides)	
K051 – API separator sludge from the petroleum refining industry	Chromium (total) Lead (Organics, Nickel, Cyanides)	1.7 –	Stabilization (lead); solvent extraction or incineration (organics)	0.20 0.037	Chemical precipitation (lead); chromium reduction, chemical precipitation, vacuum filtration (chromium); incineration (organics)	
K052 – Tank bottoms (leaded) from the petroleum refining industry	Chromium (total) Lead (Organics, Nickel, Cyanides)	1.7 –	Solvent extraction or incineration (organics); stabilization of ash	0.20 0.037	Chromium reduction, chemical precipitation, vacuum filtration (metals); incineration (cyanides)	

TABLE E-3. (continued)

Hazardous Waste Description/Code	Constituents of Concern (Remaining Constituents)	Concentration-Based Standard for Nonwastewater		Concentration-Based Standard for Wastewater		Treatment Method Specified for Technology-Based Standard
		TCLP (mg/L)	BDAT	Total Composition (mg/L)	BDAT	
K061 – Emission control dust/sludge from the primary production of steel in electric furnaces						
• High zinc subcategory (≥ 15% zinc)	Cadmium Chromium (total) Lead (Nickel)	0.14 5.2 0.24	(Treatment method specified)	1.61 0.32 0.51	Chromium reduction, chemical precipitation with lime and sulfides, sludge dewatering; chemical precipitation with magnesium hydroxide, filtration (lead)	Thermal recovery
• Low zinc subcategory (< 15% zinc)(c)	Cadmium Chromium (total) Lead (Nickel)	0.14 5.2 0.24	Stabilization	1.61 0.32 0.51	Chromium reduction, chemical precipitation with lime and sulfides, sludge dewatering; chemical precipitation with magnesium hydroxide, filtration (lead)	
K062 – Spent pickle liquor generated by steel finishing operations at facilities within the iron and steel industry (SIC codes 331 and 332)	Chromium (total) Lead (Nickel)	0.094 0.37	Chromium reduction, chemical precipitation, filtration, sludge dewatering	0.32 0.04	Separate BDAT for wastewaters not specified	
K069 – Emission control dust/sludge from secondary lead smelting						
• Calcium sulfate subcategory	Cadmium Lead	0.14 0.24	Stabilization	1.6 0.51	Chemical precipitation with lime and sulfides (cadmium); chemical precipitation with magnesium hydroxide (lead)	
• Non-calcium sulfate subcategory	Cadmium Lead		(Treatment method specified)	1.6 0.51	Chemical precipitation with lime and sulfides (cadmium); chemical precipitation with magnesium hydroxide (lead)	Thermal recovery

TABLE E-3. (continued)

Hazardous Waste Description/Code	Constituents of Concern (Remaining Constituents)	Concentration-Based Standard for Nonwastewater		Concentration-Based Standard for Wastewater		Treatment Method Specified for Technology-Based Standard
		TCLP (mg/L)	BDAT	Total Composition (mg/L)	BDAT	
K071 – Brine purification muds from the mercury cell process in chlorine production, where separately purified brine is used	Mercury	0.025	Acid leaching, chemical oxidation, dewatering	0.030	Sulfide precipitation, filtration	
K084 – Wastewater treatment sludges generated during the production of veterinary pharmaceuticals from arsenic or organo-arsenic compounds	Arsenic	5.6	Vitrification	0.79	Chemical precipitation	
K086 – Solvent washes and sludges; caustic washes and sludges, or water washes and sludges from cleaning tubs and equipment used to formulate ink from pigments, driers, soaps, and stabilizers containing chromium and lead	Chromium (total) Lead (Organics, Cyanides)	0.094 0.37	Chromium reduction, lime precipitation, filtration (metals); incineration (organics)	0.32 0.037	Chromium reduction, lime precipitation, filtration (metals); alkaline chlorination (cyanides)	
K087 – Decanter tank tar sludge from coking operations	Lead (Organics)	0.51	Rotary kiln incineration, stabilization of ashes	0.037	Chemical precipitation, filtration	

TABLE E-3. (continued)

Hazardous Waste Description/Code	Constituents of Concern (Remaining Constituents)	Concentration-Based Standard for Nonwastewater		Concentration-Based Standard for Wastewater		Treatment Method Specified for Technology-Based Standard
		TCLP (mg/L)	BDAT	Total Composition (mg/L)	BDAT	
K100 – Waste leaching solution from acid leaching of emission control dust/sludge from secondary lead smelting	Cadmium Chromium (total) Lead	0.066 5.2 0.51	Stabilization	1.6 0.32 0.51	Chromium reduction, lime and sulfide precipitation (cadmium and chromium); chemical precipitation with magnesium hydroxide (lead)	
K101 – Distillation tar residues from the distillation of aniline-based compounds in the production of veterinary pharmaceuticals from arsenic or organo-arsenic compounds	Arsenic Cadmium Lead Mercury (o-Nitroanaline)	5.6 – – –	Vitrification	0.79 0.24 0.17 0.082	Chemical precipitation	
K102 – Residue from the use of activated carbon for decolorization in the production of veterinary pharmaceuticals from arsenic or organo-arsenic compounds	Arsenic Cadmium Lead Mercury (o-Nitrophenol)	5.6	Vitrification	0.79 0.24 0.17 0.082	Chemical precipitation	

TABLE E-3. (continued)

Hazardous Waste Description/Code	Constituents of Concern (Remaining Constituents)	Concentration-Based Standard for Nonwastewater		Concentration-Based Standard for Wastewater		Treatment Method Specified for Technology-Based Standard
		TCLP (mg/L)	BDAT	Total Composition (mg/L)	BDAT	
K106 – Wastewater treatment sludge from the mercury cell process in chlorine production						
• High-mercury subcategory (≥ 260 mg/kg)	Mercury	–	(Treatment method specified)	0.030	Chemical precipitation with sulfides	Thermal recovery(b)
• Low-mercury subcategory (< 260 mg/kg)	Mercury	0.025(d) 0.020(d,e)	Acid leaching and chemical precipitation	0.030	Chemical precipitation with sulfides	
P010 – Arsenic acid (H_3AsO_4)	Arsenic	5.6	Vitrification	0.79	Chemical precipitation	
P011 – Arsenic oxide (As_2O_5)	Arsenic	5.6	Vitrification	0.79	Chemical precipitation	
P012 – Arsenic oxide (As_2O_3)	Arsenic	5.6	Vitrification	0.79	Chemical precipitation	
P036 – Dichlorophenylarsine	Arsenic	5.6	Vitrification	0.79	Chemical precipitation	
P038 – Diethylarsine	Arsenic	5.6	Vitrification	0.79	Chemical precipitation	
P065 – Mercury fulminate						
• High-mercury subcategory (≥ 260 mg/kg)	Mercury	–	(Treatment method specified)	0.030	Chemical precipitation with sulfides	Thermal recovery(b)
• Low-mercury subcategory (< 260 mg/kg)	Mercury	0.20(d) 0.025(d)	Acid leaching Chemical precipitation	0.030	Chemical precipitation with sulfides	

TABLE E-3. (continued)

Hazardous Waste Description/Code	Constituents of Concern (Remaining Constituents)	Concentration-Based Standard for Nonwastewater		Concentration-Based Standard for Wastewater		Treatment Method Specified for Technology-Based Standard
		TCLP (mg/L)	BDAT	Total Composition (mg/L)	BDAT	
P092 – Phenyl-mercuric acetate						
• High-mercury subcategory (≥ 260 mg/kg)	Mercury	–	(Treatment method specified)	0.030	Chemical precipitation with sulfides	Thermal recovery(b)
• Low-mercury subcategory (< 260 mg/kg)	Mercury	0.20(d) 0.025(d)	Acid leaching Chemical precipitation	0.030	Chemical precipitation with sulfides	
P110 – Tetraethyl lead	Lead (Organics)	0.51	Stabilization (lead); incineration organics)	0.040	Chemical precipitation, filtration, settling	
U032 – Calcium chromate	Chromium (total)	0.094	Chromium reduction, lime or sulfide precipitation, sludge dewatering	0.32	Chromium reduction, lime or sulfide precipitation, sludge dewatering	
U051 – Creosote	Lead (Organics)	0.51	Stabilization (lead); incineration (organics)	0.037	Chemical precipitation (lead); incineration (organics)	
U136 – Cacodylic acid	Arsenic	5.6	Vitrification	0.79	Chemical precipitation	
U144 – Lead acetate	Lead	0.51	Incineration followed by stabilization	0.040	Chemical oxidation followed by chemical precipitation	
U145 – Lead phosphate	Lead	0.51	Incineration followed by stabilization	0.040	Chemical oxidation followed by chemical precipitation	
U146 – Lead subacetate	Lead	0.51	Incineration followed by stabilization	0.040	Chemical reduction, lime or sulfide precipitation, sludge dewatering	

TABLE E-3. (continued)

Hazardous Waste Description/Code	Constituents of Concern (Remaining Constituents)	Concentration-Based Standard for Nonwastewater		Concentration-Based Standard for Wastewater		Treatment Method Specified for Technology-Based Standard
		TCLP (mg/L)	BDAT	Total Composition (mg/L)	BDAT	
U151 - Mercury • High-mercury subcategory (≥ 260 mg/kg)	Mercury	—	(Treatment method specified)	0.030	Chemical precipitation with sulfides	Thermal recovery[b]
• Low-mercury subcategory (< 260 mg/kg)	Mercury	0.20[d] 0.025[d]	Acid leaching, chemical precipitation	0.030	Chemical precipitation with sulfides	

(a) D008 lead acid battery standard only applies to lead acid batteries that are identified as RCRA hazardous wastes and that are not excluded elsewhere from regulation under the LDRs of 40 CFR Part 268 or exempted under other EPA regulations (see 40 CFR 266.80).

(b) Mercury-containing nonwastewaters are subject to two specified treatment methods if they are in the high-mercury subcategory (i.e., ≥ 260 mg/kg total mercury). If the nonwastewaters are inorganic, they must be roasted or retorted. If they contain organics, one additional option of incineration is allowed; the incinerator residues would have to be roasted/retorted if they contain ≥ 260 mg/kg total mercury. P065 nonwastewaters must be incinerated; if the incinerator residues contain ≥ 260 mg/kg total mercury, they must be roasted or retorted. P092 nonwastewaters may be incinerated (if they contain organics) or roasted/retorted; residues from either process must be roasted/retorted if they contain ≥ 260 mg/kg total mercury. Incinerator residues (not retorting/roasting residues) containing < 260 mg/kg total mercury must meet a TCLP mercury standard of 0.025 mg/L. Roasting/retorting residues containing < 260 mg/kg total mercury must meet a TCLP mercury standard of 0.20 mg/L.

(c) The EPA has proposed combining high- and low-zinc subcategories with metal recovery as BDAT, see 57 FR 958, January 9, 1992.

(d) Low-mercury subcategory – less than 260 mg/kg Hg [K106, P065, P092, and U151]. For low-mercury subcategory, the nonwastewater standard of 0.025 mg/L applies to nonwastewaters that are not residues from mercury retorting or roasting. The 0.20 mg/L standard applies to nonwastewater residues from retorting or roasting.

(e) The mercury standard of 0.020 established by the 1/31/91 technical amendment (56 FR 3882) appears to be a typographical error. The correct value is believed to be 0.20 mg/L [K106].

Prior to land ban, most arsenic wastes were managed by disposal to a hazardous waste landfill. The U.S. EPA considered incineration, stabilization, and vitrification as demonstrated technologies for arsenic-bearing nonwastewaters. Incineration would transfer arsenic to ash or slag that would probably require further treatment. A variety of stabilization techniques including cement, silicate, and pozzolan and ferric coprecipitation were evaluated. Due to concerns about long-term stability and the waste volume increase, particularly with ferric coprecipitation, stabilization was not accepted as BDAT.

The U.S. EPA BDAT analysis recognized the theoretical possibility of recovering arsenic trioxide from incineration or other thermal processes due to its low sublimation temperature of 193°C (380°F). The U.S. EPA identified a copper smelter in Canada that was being considered for accepting wastes from the wood-preserving industry. The wastes would be processed in the smelter to recover, for sale, arsenic trioxide. One wood-preserving plant was identified that used arsenic-bearing lead smelter flue dust containing about 50% arsenic to produce arsenic acid. However, the U.S. EPA determined that, although possible, arsenic recovery is not sufficiently attractive economically to be generally available (U.S. EPA, 1990, EPA/530-SW-90-059A).

The U.S. EPA considered chemical precipitation, ion exchange, and carbon adsorption as demonstrated technologies for removal of arsenic from wastewaters. Reliable performance data were available only for precipitation processes. The U.S. EPA did not believe that ion exchange or carbon adsorption would offer improved performance. Therefore, treatment standards for the wastewater forms of arsenic wastes are established based on chemical precipitation. The concentration-based standard is set at the toxicity characteristic concentration level (5.0 mg/L) (U.S. EPA, 1990, EPA/530-SW-90-59A).

E.2 BEST DEMONSTRATED AVAILABLE TECHNOLOGIES FOR CADMIUM WASTES

Cadmium nonwastewaters are regulated at the toxicity characteristic level (1.0 mg/L) based on metal recovery or stabilization depending on the waste type. BDATs are identified for two subcategories of D006 (cadmium characteristic) nonwastewaters:

- cadmium-containing batteries
- nonwastewater (other than cadmium-containing batteries).

The U.S. EPA considered stabilization and incineration as demonstrated technologies for cadmium nonwastewaters. Stabilization was selected as BDAT for all cadmium nonwastewaters other than cadmium-containing batteries (U.S. EPA, 1990, EPA/SW/530/90-059U).

The BDAT for cadmium-containing batteries is thermal recovery (55 *FR* 22562 June 1, 1990). The U.S. EPA determined that a well-designed and well-operated pyrometallurgical recovery process can treat D006 wastes such that the concentration levels of cadmium in the furnace residues are allowable for land disposal under Section 3004(m) of the Hazardous and Solid Waste Amendments (HSWA). Air pollution control for the process may produce wastewater and nonwastewater forms of D006 wastes. Any such wastes that have the TCLP toxicity levels for D006 wastes are not considered to be in the battery subcategory. These air pollution control wastes are instead considered D006 wastes other than batteries and must meet the applicable treatment standards (U.S. EPA, 1990, EPA/SW/530/90-059U).

The U.S. EPA found data indicating that pyrometallurgical recovery could be applied to forms of cadmium nonwastewaters in addition to the battery subcategory. Recovery is preferred over treatment for wastes with cadmium concentrations similar to the concentrations in batteries. The U.S. EPA was, however, unable to establish a concentration level for economic high-temperature cadmium recovery from nonbattery nonwastewaters. In the absence of an established limit, stabilization was determined to be the best technology for all D006 nonwastewaters other than batteries.

Both pyrometallurgical and hydrometallurgical processes for recovery of cadmium are described in the literature. Despite the availability of hydrometallurgical processes, established commercial processes rely mainly on pyrometallurgy to recover cadmium. Pyrometallurgical processing of cadmium presents several challenges. Molten cadmium metal is corrosive and tends to form a finely divided oxide fume that is difficult to remove from the process off-gas. The hydrometallurgical processes avoid handling molten cadmium metal but also have limitations. Hydrometallurgical processing requires a sequence of processing operation in separate vessels and produces a variety of wastewater streams requiring special treatment.

Cadmium can be recovered from solid wastes by heating the waste material to vaporize cadmium. The operating temperature is typically about 800 to 1200°C (1470 to 2200°F). A reducing agent is supplied in the melt to release cadmium metal. The atmosphere over the melt may be operated in the oxidizing mode to give cadmium oxide or in the reducing mode to give cadmium metal. If the starting material is whole batteries, the residue will have high iron and nickel levels and may be marketed as high-grade metal scrap (Cole and Carr, 1986).

For large rectangular cells it may be economical to disassemble the battery prior to feeding it to the furnace. The positive plates contain about 18% nickel and less than 0.5% cadmium. It may be possible to remove the positive plates for disposition as scrap without additional processing. The negative plates, which contain 10 to 25% cadmium, can be fed to the processing furnace.

Smaller sealed cells typically are fed directly to the furnace. The furnace is held at 400°C (750°F) to destroy the plastic in the cases before proceeding with the higher temperature processing to recover the cadmium (Anulf, 1989).

Treatment standards for the wastewater forms of cadmium wastes are established based on chemical precipitation. The concentration-based standard is set at the toxicity characteristic concentration level (1.0 mg/L).

E.3 BEST DEMONSTRATED AVAILABLE TECHNOLOGIES FOR CHROMIUM WASTES

Both trivalent and hexavalent chromium are regulated for wastes with a total TCLP chromium level over 5.0 mg/L. The treatment standard is established as the toxicity characteristic concentration level (5.0 mg/L).

The U.S. EPA considered stabilization and metal recovery as demonstrated technologies for chromium nonwastewaters. Stabilization was established as the BDAT for chromium nonwastewaters such as D007 (chromium characteristic) and U032 (chromic acid).

The U.S. EPA considered thermal processing to recover chromium as a possible BDAT for the refractory bricks subcategory of D007 wastes. The U.S. EPA determined that the International Metals Reclamation Corporation (INMETCO) recovers chromium from refractories by high-temperature thermal processing. The U.S. EPA reports that recovery technology is used for bricks containing up to 20% chromium and believes it can treat bricks containing up to 40% chromium. The presence of phosphate impurities reduces the quality of the recovered chromium product. (See the discussion of pyrometallurgical processing in Subsection 4.4.1.2 for more detail on the INMETCO process.) The U.S. EPA determined that thermal recovery is an alternative for some forms of refractory bricks. However, the agency was unable to establish the general applicability of thermal recovery to all types of refractory bricks and, therefore, did not establish thermal recovery as the BDAT (U.S. EPA, 1990, EPA/530-SW-90-59V).

Treatment standards for the wastewater forms of chromium wastes are established based on chromium reduction followed by chemical precipitation (U.S. EPA, 1990, EPA/530-SW-90-59V).

E.4 BEST DEMONSTRATED AVAILABLE TECHNOLOGIES FOR LEAD WASTES

The BDAT standards for D008 (lead characteristic) nonwastewaters, except explosive compounds and wastes from the recycling of lead-acid batteries, are based on stabilization or vitrification. For the lead-acid battery subcategory of D008, where the batteries are hazardous waste and are not exempt, the BDAT standard is thermal recovery in secondary lead smelters.

The BDAT for P110 (tetraethyl lead), U144 (lead acetate), U145 (lead phosphate), and U146 (lead subacetate) nonwastewaters is stabilization for inorganics and incineration (and stabilization of the ash if needed) for organolead wastes.

The BDAT for K069 (emission control dust/sludge from secondary lead smelting) nonwastewaters in the noncalcium sulfate subcategory is thermal recovery in secondary lead smelters (55 *FR* 22573, June 1, 1990). The noncalcium sulfate subcategory is defined as those emission control sludges from secondary lead smelting that are not generated as calcium sulfate from secondary wet scrubbers using lime neutralization (53 *FR* 31165, August 17, 1988).

Selection of BDAT for lead nonwastewater was based on lead recovery, incineration, and stabilization as demonstrated technologies. The U.S. EPA noted that a variety of nonwastewater forms of D008 as well as K061 wastes with up to 50,000 mg/kg of lead can be treated by thermal recovery methods. The resulting residues have a leachate concentration of lead below the characteristic level of 5 mg/L. Some consideration was given to establishing recovery as the BDAT for inorganic nonwastewater lead wastes containing 2.5% or more lead. Commentors on the proposal indicated that a lead concentration of 25% would be required for lead recovery to be economical (55 *FR* 22565, June 1, 1990). Most feedstocks are >65% for economical lead recovery. The agency also noted that not all forms of D008 are readily amenable to recovery processes. Lead may be present in refractory solid matrices making extraction difficult (U.S. EPA, 1990, EPA/530-SW-90-059W). As a result, lead recovery was established as BDAT only for the D008 lead acid battery subcategory.

Treatment standards for the wastewater forms of lead wastes are established based on chemical precipitation. The concentration-based standard is set at the toxicity characteristic concentration level (5.0 mg/L) (U.S. EPA, 1990, EPA/530-SW-90-059W).

E.5 BEST DEMONSTRATED AVAILABLE TECHNOLOGIES FOR MERCURY WASTES

Different BDATs were identified as applicable in four general types of mercury wastes:

- high-mercury nonwastewaters
- low-mercury nonwastewaters
- organic mercury nonwastewaters
- mercury wastewaters.

The U.S. EPA study indicated that mercury is difficult to reliably stabilize when present either at high concentration or in elemental form. The analysis of treatability data did, however, indicate that low concentrations of elemental mercury could be stabilized to meet the leachability levels acceptable for land disposal.

Due to the concerns about the ability to stabilize wastes containing high levels of mercury, the U.S. EPA examined a range of extraction and concentration techniques for recovery of mercury for reuse. The classical technologies for recovery of mercury from sludges are roasting or retorting. These are thermal processes that sublimate mercury from metal-bearing wastes and capture mercury for further refining prior to reuse. Aqueous-based mercury recovery methods also were considered, including acid leaching to form a solution which is then further concentrated by amalgamation, ion exchange, electrodialysis, or electrowinning. Mercury concentrated by the amalgamation or ion exchange unit will require further treatment such as roasting followed by triple vacuum distillation to produce a refined product (U.S. EPA, 1990, EPA/530-SW-90-59Q).

Due to a lack of data on mercury waste treatment by acid leaching followed by solution processing, the U.S. EPA established roasting and retorting as the BDAT for all mercury nonwastewaters having total mercury concentrations above 260 mg/kg, except for radioactive mixed wastes. The affected RCRA wastes are D009 (mercury characteristic), P065 (mercury fulminate), P092 (phenylmercuric acetate), U151 (mercury), and K106 (wastewater treatment sludge from the mercury cell process in chlorine production). The U.S. EPA also established incineration as a pretreatment step for P065, P092, and D009 (organics) prior to retorting in its June 1, 1990 rule (June 1, 1990, 55 *FR* 22572 and 22626).

The BDAT technology code RMERC is defined as retorting or roasting in a thermal processing unit capable of volatilizing mercury and subsequently condensing the volatilized mercury for recovery. The retorting or roasting unit (or facility) must be subject to one or more of the following:

- a National Emissions Standard for Hazardous Air Pollutants (NESHAP) for mercury
- a Best Available Control Technology (BACT) or a Lowest Achievable Emission Rate (LAER) standard for mercury imposed pursuant to a Prevention of Significant Deterioration (PSD) permit
- a state permit that establishes emission limitations (within the meaning of section 302 of the Clean Air Act) for mercury.

All wastewater and nonwastewater residues derived from this process must then comply with the corresponding treatment standards per waste code with consideration of any applicable subcategories (e.g., high- or low-mercury subcategories).

The U.S. EPA determined that acid leaching is the only demonstrated treatment technology available for inorganic mercury nonwastewaters with a total mercury content below the thermal recovery limit. Acid leaching solubilizes low concentrations of mercury in wastes, reducing the concentration of mercury in the nonwastewater residuals. The mercury in the acid leachate must then be treated to precipitate mercury as in the mercury wastewater category.

BDAT treatment standards for organomercury nonwastewaters require pretreatment to remove or destroy the organic material. The organic constituents may interfere with the recovery or treatment of mercury-bearing wastes. Ash and off-gas treatment residuals from the incinerator must be treated by the BDAT specified. These residuals may be inorganic high- or low-mercury nonwastewaters (depending on the mercury concentration) and/or mercury-containing wastewaters.

The U.S. EPA identified chemical precipitation followed by filtration, carbon adsorption, and ion exchange as demonstrated technologies for treatment of mercury-containing wastewaters where the mercury content is in an inorganic form. The U.S. EPA identified chemical oxidation followed by chemical precipitation followed by filtration, carbon adsorption, and ion exchange as demonstrated technologies for treatment of mercury-containing wastewaters containing organomercury content or inorganic mercury in an organic matrix. Mercury typically is precipitated as the sulfide at an alkaline pH (U.S. EPA, 1990, EPA/530-SW-90-59Q).

E.6 BEST DEMONSTRATED AVAILABLE TECHNOLOGIES FOR STEELMAKING WASTE

The approximate annual production of dust from steelmaking is 1.8 × 10^6 metric tons (2 × 10^6 tons). The dust comes from one of three furnace types:

- basic oxygen furnace
- electric arc furnace
- open hearth furnace.

About 0.45 × 10^6 metric tons (0.5 × 10^6 tons) of the dust is produced by electric arc furnaces (Collins, 1991). In the electric arc furnace, less than 2% of the input is converted to dust. An off-gas treatment system, typically using scrubbers and baghouse filters, captures the dust. Furnaces processing carbon and low-alloy steels recycle more galvanized or terne-coated scrap than do furnaces processing stainless or high-alloy steels. The dust from furnaces processing lower alloy, therefore, tends to have higher zinc and lead concentrations. The dust from carbon and low alloy steel contains about 11 to 30% zinc and about 1 to 4% lead. The zinc and lead levels in electric arc furnace (EAF) dust from higher alloy steels typically are 2 to 6% and 0.23 to 0.78%, respectively (Krishnan, 1983). EAF dust is listed as a RCRA hazardous waste and is covered by BDAT standards.

Nonwastewaters listed as K061 (emission control dust/sludge from the primary production of steel in electric furnaces) are divided into two subcategories (U.S. EPA, 1988, EPA/350-SW-88-031D):

- low zinc (<15% zinc)
- high zinc (>15% zinc).

The BDAT for the high zinc subcategory is high-temperature metals recovery (HTMR). Nonwastewater residuals from HTMR of K061 waste are granted a generic exclusion from land ban restrictions as long as they meet concentration requirements, are disposed of in units as specified in Subtitle D, and do not exhibit hazardous characteristics (56 *FR* 41164, August, 1991). The U.S. EPA reports that a significant fraction of the emission control nonwastewaters is in the high-zinc subcategory. The BDAT for the low-zinc subcategory is stabilization (55 *FR* 22599, June 1, 1990).

After the First Third rulemaking, the U.S. EPA received data and comments concerning the decision to divide K061 based on zinc content. Commentors indicated that K061 wastes with zinc contents less than 15% were processed for zinc recovery. In addition, data were submitted indicating that other metals such as chromium or nickel could be recovered from K061 wastes. As a result, the U.S. EPA has proposed eliminating the 15% cutoff for K061 wastes (57 *FR* 974, January 9, 1992).

Metal-bearing wastes also are generated by acid conditioning of steel. Wastes from spent pickle liquor generated by steel finishing operations of facilities within the iron and steel industry (SIC 331 and 332) are listed as K062. The U.S. EPA received a comment indicating that K062 nonwastewaters can be treated by HTMR. The U.S. EPA was unable to sufficiently verify the applicability of metals recovery from K062 nonwastewater to allow development of treatment standards (53 *FR* 31164, August 17, 1988). Standards for nonwastewater K062 wastes are developed on the basis of chromium reduction, sulfide precipitation, settling, filtering, and dewatering (U.S. EPA, 1988, EPA/530-SW-88-031E).

Based on additional data, the U.S. EPA has proposed HTMR as an alternative standard for K062 nonwastewaters. The metal recovery standard is not proposed as a replacement for the existing stabilization standard. The U.S. EPA also has proposed a generic exclusion of nonwastewater residuals from HTMR of K062 wastes similar to the exclusion for K061 residuals (57 *FR* 960, January 9, 1992).

E.7 BEST DEMONSTRATED AVAILABLE TECHNOLOGIES FOR PLATING WASTES

Treatment standards for F006 nonwastewaters were derived from performance data for stabilization. The U.S. EPA examined recycling as a candidate BDAT for F006 (wastewater treatment sludges from nonexempted electroplating operations). Stabilization and metal recovery were considered as demonstrated technologies for plating wastes (U.S. EPA, 1988, EPA/530-SW-88-031L). The U.S. EPA reports some indications of success in recovery of metals from metal-bearing sludges. However, the Agency noted that the metal concentrations and form and matrix composition vary depending on the plating process. Recovery is unlikely to be generally applicable to all electroplating sludges. The U.S. EPA was not able to define a subcategory of electroplating wastes that would be amenable to recovery and, therefore, did not establish metals recovery as the BDAT (53 *FR* 31153, August 17, 1988). However, comments and data submitted to the U.S. EPA indicate that HTMR is applicable to certain electroplating sludges. Therefore, HTMR was proposed as an alternative standard for F006 nonwastewaters. The metal recovery standard is not proposed as a replacement for the existing stabilization standard. The U.S. EPA also has proposed a generic exclusion of nonwastewater residuals from HTMR of F006 wastes similar to the exclusion for K061 residuals (57 *FR* 960, January 9, 1992).

Treatment standards for cadmium, total chromium, lead, and nickel in F006 wastewaters were developed based on treatability data for chromium reduction followed first by chemical precipitation using lime and sulfide and then by sludge dewatering (U.S. EPA, 1990, EPA/530-SW-90-059M).

E.8 BEST DEMONSTRATED AVAILABLE TECHNOLOGIES FOR PIGMENT WASTES

Wastes listed as K002, K003, K004, K005, K006, K007, and K008 are generated from the production of inorganic pigments. These wastes are designated as:

K002 Wastewater treatment sludge from the production of chrome yellow and orange pigments

K003 Wastewater treatment sludge from the production of molybdate orange pigments

K004 Wastewater treatment sludge from the production of zinc yellow pigments

K005 Wastewater treatment sludge from the production of chrome green pigments

K006 Wastewater treatment sludge from the production of chrome oxide green pigments (anhydrous and hydrated)

K007 Wastewater treatment sludge from the production of iron blue pigments

K008 Oven residues from the production of chrome oxide green pigments.

The K002, K003, K004, K005, K006, K007, and K008 wastes contain chromium and some of the wastes, such as K002, K003, and K005, also contain lead. The BDAT standards for metal constituents in K002, K003, K004, K005, K006 (anhydrous), K007, and K008 nonwastewaters are based on the performance of chemical precipitation, sludge dewatering, and filtration. BDAT for chromium in hydrated K006 is based on the performance of stabilization of F006 wastes. The treatment standards for cyanide in K005 and K007 nonwastewaters are being developed (55 *FR* 22583, June 1, 1990).

The U.S. EPA identified one facility recycling a mixed K002/K003 waste. The recycle process involves the addition of lead salts to the process wastewater to precipitate a high lead sludge. The sludge contains lead chromate and lead carbonate forming a synthetic analog of the natural lead-bearing minerals crocoite and cerussite. A lead smelter buys the sludge as a substitute for its normal lead-bearing scrap feedstock. The BDAT review also noted that the chromium hydroxide solids generated by wastewater treatment wastestreams from chrome green pigments can be recycled directly back to the pigment production process. However, the U.S. EPA believed that recycling opportunities would be waste- and plant-specific and did not give a sufficient basis for establishing recycling as the BDAT (U.S. EPA, 1990, EPA/530-SW-90-059Y).

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APPENDIX F

REVIEW OF METAL RECYCLING OPTIONS FOR METAL-CONTAMINATED WASTES FROM CERCLA SITES

A variety of options are available to recycle solid materials contaminated with metals. These recycling options will be in competition with conventional and innovative offsite and onsite treatment methods. The site logistics, waste matrix type, waste composition, economics, and regulatory requirements all influence the attractiveness of recycling alternatives (Bishop and Melody, 1993). Recycling usually entails a creative search of users for what would otherwise be waste materials.

F.1 CONTAMINANT COMPOSITION

The contaminant composition is a major consideration in selection of a recycling option. The critical features of waste composition are:

- The type and concentration of metal
- Additional processing that may make waste suitable for reuse
- Other metals in the waste that may complicate recovery or reuse
- Inorganic salts in the waste that may complicate recovery or reuse
- Organics in the waste that may complicate recovery or reuse

F.2 WASTE MATRIX EFFECTS

Review of waste matrix effects should consider:

- Waste matrix compatibility with the existing recycling processing techniques and equipment
- Waste matrix compatibility with the intended end use
- Waste matrix effects on contaminant mobility
- Value of the matrix as a bulk commodity

F.3 SITE CHARACTERISTICS

Some site characteristics may favor or hinder recycling independent of the contaminant or matrix. These factors can be generally characterized as removal logistics. Removal logistics considers the feasibility of excavation, handling, and transporting the contaminated solid. Examination of removal logistics is directed at answering questions such as:

- Accessibility of the materials for excavation

- Ability to move the contaminated solid efficiently by conventional bulk material handling equipment and techniques

- Availability of onsite and offsite infrastructure for transportation of waste materials

F.4 ECONOMIC FACTORS

Economic factors play a major role in the identification and selection of recycling options.

F.4.1 Operating and Capital Costs

The selection of a recycling option will be based on economics. The economic analysis will need to consider the overall cost of the recycling versus treatment and disposal.

- Potential cost recovery of recycling option
- Consideration of life-cycle factors can improve the competitive position of recycling
- Intangible factors may be favorable to recycling
- Recycling can require major investment of capital

If a paying recycling market is identified for the metal-bearing material, treatment and disposal should not be considered. The value or cost of recycling a metal-bearing material will be determined by competition with other raw materials in the marketplace.

For most of the materials covered in the scope of this document there will be a fee associated with recycling. Recycling options will then need to be evaluated in competition with treatment and disposal alternatives, except where treatment and disposal is precluded by land ban requirements. The economic analysis should include both direct costs and avoided expenses through the life-cycle of the alternative considered. In addition, intangible factors such as improved public image or the potential for liability should be considered.

The relative capital costs can also influence a decision. Even if one option if favorable overall, a more costly option with lower capital cost may be chosen due to limited availability of capital.

F.4.2 Recycling Market

Potentially recyclable material must face competition from conventional materials filling the same needs. The competitive position of the contaminated material needs to be considered to address questions such as:

- Shipping distance between site and markets
- The volume of material available in relation to market supply and demand

The location of the site and the volume of material can influence the economic viability of recycling. Location near an end user will reduce shipping costs.

Both the matrix composition and the contaminant levels in the wastestreams can be highly variable. Industrial users prefer a steady supply of consistent materials. The desire for a homogeneous feedstock is often not consistent with the realities of waste production. If possible, preprocessing the waste to improve homogeneity is one approach to improving market acceptance. Table F-1 tabulates the apparent consumption and amounts of recycling for some metals in the U.S. economy.

F.5 APPROACH TO SELECTION OF RECYCLING OPTIONS

The following discussion of recycling options and how to identify and evaluate them is intended to set a few guidelines. These discussions can give a preliminary idea of the possible markets for metal-bearing material and start the search for recycling options. The analysis is a complex task which must be prepared for a specific waste type. Due to the lack of clear definition of what constitutes valid recycling, the user needs to be particularly careful when identifying options for hazardous material recycling. The ultimate interpretation rests with the Federal, State, and local regulators.

TABLE F-1. DATA ON USE AND RECYCLING OF SELECTED METALS IN THE UNITED STATES

Metal	New Scrap Recycle[a] (metric tons)	Old Scrap Recycle[b] (metric tons)	Total Recycle (metric Tons)	Apparent Consumption[c] (metric tons)	Recycle (%)	Metal Price Range in Reporting Year ($/metric ton)	Reporting Year
Arsenic	None	None	None	20,700	0	[d]	1990
Cadmium	No Data	No Data	Small	3,100	Small	5,950	1990
Chromium	No Data	No Data	No Data	423,000	[e]	7,830	1990
Copper	679,882	533,338	1,213,220	2,783,000	44	2,650 to 2,100	1991
Lead	54,172	829,563	883,735	1,246,000	71	770 to 700	1991
Mercury	No Data	217[f]	No Data	720	14[f]	8,490 to 5,295	1990
Nickel	No Data	No Data	32,520	128,050	25	9,215 to 7,030	1991
Zinc	233,000	120,000	353,000	1,134,000	31	1,540 to 1,370	1991

(a) New scrap is scrap resulting from the manufacturing process including metal and alloy production.
(b) Old scrap is scrap resulting from consumer products.
(c) Apparent consumption is production plus imports plus stock changes.
(d) Arsenic prices are not easily available from published sources. Mexican arsenic trioxide cost in 1990 was about $500/metric ton and has been generally declining. The cost spread between high and low grade oxide is typically about $220/metric ton. Chinese metal supply (for lead alloys) has fluctuated resulting in large price savings for arsenic metal.
(e) Recycling of chromium in stainless steel filled about 21 percent of the total chromium demand.
(f) Average annual recycling between 1985 and 1989.
No Data = No data available.

Source: Compiled from Jolly et al., 1993; Espinosa, 1993; Bureau of Mines, 1993; and Bureau of Mines, 1991.

Once the potential markets are identified, some basis must be found for establishing specifications for materials. Reliable materials commerce requires some acceptable standards describing the composition, quality, and properties of recycled materials. The specifications may be based on the material origin, composition, end use performance, or other characteristics. Potential end users may avoid recycled material if they are uncertain about the impurity levels or how well the quality of the material will be controlled (van den Berg, 1991).

In general, developing a specification will require negotiation between the supplier and user. Some guidance is available. ASTM or other specifications include or can be applied to recycled materials. EPA under the provisions of RCRA are encouraging government agencies to allow use of recycled materials. However, most existing specifications are written to ignore or possibly even preclude recycled materials. Creative use of existing specifications may be needed to reach a definition of material composition and properties that is acceptable to the buyer and seller.

Material characterization for recycling requires a somewhat different outlook and approach than is typical for waste treatment studies. Waste characterization for waste treatment and disposal usually focuses mainly on the amount of contaminant present. The mineral form of the contaminant and the composition and form of the matrix are considered only in light of how they may affect performance of treatment or disposal options. Recycling requires thinking of the entire body of waste material as a product. As a result, its total composition, chemical speciation, and physical form need to be established early in the characterization process.

Waste materials, particularly those from CERCLA sites, usually have highly variable compositions. End users prefer a reliable stream of materials with predictable composition. The waste supplier may, therefore, need to provide pretreatment to homogenize and sample the material to prepare a product that is acceptable for the user.

In the face of competition from traditional raw materials sources, the waste generator or supplier often needs to take an active role to seek out uses for the waste material. Recycling can succeed only if there are markets for the waste material. In general, users of recycled materials are in a buyer's market. A large new source of waste materials available for recycling can saturate end-use markets. Elements that can help in finding uses for waste materials are:

- Established and effective specifications
- Creative effort to identify possible uses
- Providing a reliable supply of consistent material
- Programs to improve public awareness of recycling potential

Table F-2 provides a review of recyclers of metal-contaminated wastes from CERCLA sites. Following the table is a list of the names and addresses of the recyclers given in the headings in Table F-2. Vendors of recycling services were surveyed to provide RMs with specific information sources on possible alternatives. The listing is as complete as possible. Due to the extent and dynamic nature of the waste treatment field, some recycling companies probably have been overlooked in this survey. Mention of specific companies is not intended as an endorsement. The permit or environmental compliance status of the listed companies was not investigated by the authors of this report. Superfund site wastes sent offsite must be sent to properly permitted and compliant facilities.

TABLE F-2. RECYCLERS OF METAL-CONTAMINATED WASTES FROM CERCLA SITES

	ASARCO East Helena, MT	Advance Environmental Recycling Corp. Allentown, PA	Alpha Omega Recycling, Inc. White Oak, TX	Bay Zinc Moxee, WA	Bethlehem Apparatus Company Hellertown, PA	CP Chemicals Fort Lee, NJ	Canonie Environmental Englewood, CO	Ceramic Bonding Mountain View, CA	CRI-MET Braithwaite, LA	Cyprus Miami Mining Claypool, AZ	Doe Run Co. Boss, MO	Doe Run Co. Herculaneum, MO	East Penn Manufacturing Co., Inc. Lyon Station, PA	Encycle Texas, Inc. Corpus Christi, TX	Elicam Providence, RI; Fernley, NV	Exide Corp. Reading, PA; Muncie, IN	GNB, Inc. Columbus, GA	Gopher Smelting and Refining Eagan, MN
Pb-Bearing Materials																		
Baghouse Filtrate											♦	♦	♦	♦		♦	♦	♦
Sludge	♦										♦			♦				
Slag	♦										♦			♦		♦		
Glass	♦										♦	♦	♦	♦		♦	♦	
Ceramics	♦										♦	♦		♦				
Pigments	♦										♦					♦		
Paint Removal Debris	♦										♦			♦		♦		
Projectiles from Soils							♦				♦	♦	♦			♦		
Superfund Soils	♦						♦				♦			♦				
Firing Range Soils	♦										♦			♦		♦		♦
Superfund Wastes											♦					♦		
Hg-Bearing Materials																		
Liquid Hg Refining		♦																
Contaminated Solids					♦													
Spill Collection Kits		♦																
Devices Made with Hg																		
Amalgams																		
RCRA Wastes																		
D001																		
D002										♦					♦			
D003										♦					♦			
D004			♦							♦								
D005			♦							♦								
D006			♦							♦					♦			
D007			♦							♦					♦			
D008			♦							♦					♦			
D009		♦[a]	♦		♦					♦								
D010			♦							♦								
D011			♦							♦					♦			
F006			♦					♦	♦[b]	♦				♦	♦			
F019			♦						♦[b]									
K061				♦														
K062																		
U151																		
D Metals Characteristic-Catalysts														♦				
Other/Mixed Metals						♦[c]												

(a) Not including soils & sludges (b) Cr-bearing sludges only (c) Recovers Ni or Cu; permitted for all D,F, or K wastes

Adapted from: *Lead Recycling Directory–1992*, used with permission of the publisher, Lead Industries Association, New York, New York.

TABLE F-2. (Continued)

	Gulf Chemical and Metallurgical Freeport, TX	Horsehead Resource Development Co. Plants in IL, PA, TN, and TX	Inorganic Service Corp. Dublin, OH	INMETCO – Int'l Metals Reclamation Co. Ellwood City, PA	Mercury Refining Company Latham, NY	Noranda Minerals Belledune, New Brunswick, Canada	Nova Lead, Inc. Ville Ste. - Catherine, Quebec, Canada	NSSI/Sources and Services Houston, TX	Parkans Intl Houston, TX	Pittsburgh Mineral and Env. Technology New Brighton, PA	Quicksilver Products Brisbane, CA	Refined Metals Corporation Memphis, TN; Beech Grove, IN	Schuylkill Metals Corporation Baton Rouge, LA; Forest City, MO	Seaview Thermal System Blue Bell, PA	Vulcan Lead Resources Milwaukee, WI	Westinghouse Electric Pittsburgh, PA	Zia Technology of Texas Caldwell, TX
Pb-Bearing Materials																	
Baghouse Filtrate						◆	◆					◆	◆		◆		
Sludge												◆					
Slag						◆	◆					◆	◆				
Glass						◆	◆					◆	◆				
Ceramics						◆	◆					◆	◆				
Pigments						◆	◆					◆					
Paint Removal Debris						◆	◆			◆[d]		◆				◆[d]	
Projectiles from Soils						◆							◆				
Superfund Soils						◆						◆					
Firing Range Soils						◆						◆					
Superfund Wastes						◆	◆						◆				
Hg-Bearing Materials																	
Liquid Hg Refining					◆			◆			◆						
Contaminated Solids					◆					◆[d]	◆			◆			
Spill Collection Kits																	
Devices Made with Hg											◆						
Amalgams																	
RCRA Wastes																	
D001				◆													
D002				◆													
D003				◆													
D004																	
D005																	
D006				◆													
D007				◆													
D008				◆													
D009					◆												
D010																	
D011																	
F006			◆[d]	◆													
F019																	
K061		◆	◆[d]	◆													◆
K062				◆													
U151					◆												
D Metals Characteristic-Catalysts	◆								◆								
Other/Mixed Metals		◆[e]						◆[f]									

(d) Provides on-site recycling system. (e) Recovers Cd, Pb, and Zn. (f) Accepts a wide range of RCRA wastes for recycling.

Adapted from: *Lead Recycling Directory–1992*; used with permission of the publisher, Lead Industries Association, New York, New York.

RECYCLERS OF METAL-BEARING WASTES

ASARCO, Inc.
Headquarters
180 Maiden Lane
New York, NY 10038
Glendon Archer
(212) 510-2215
Plant is in E. Helena, MT

Advance Environmental Recycling Corporation
2591 Mitchell Avenue
Allentown, PA 18103
Jane E. Buzzard
(215) 797-7608
(215) 797-7696

Alpha Omega Recycling, Inc.
315 South Whatley Road
White Oak, TX 75693
(903) 297-7272

Bay Zinc
Moxee, WA 98936
Robert Chase
(509) 248-4911

Bethlehem Apparatus Co.
890 Front Street
Hellertown, PA 18055
Bruce Lawrence
(215) 838-7034

CP Chemicals
ERS Division
1 Parker Plaza
Fort Lee, NJ 07024
(800) 777-1850
(201) 944-7916 Fax
Plants in CA, IL, SC, and TX

Canonie Environmental
94 Iverness Terrace East
Suite 100
Englewood, CO 80112
John A. Meardon
(303) 790-1747
(303) 799-0186 Fax

Ceramic Bonding
939 San Rafael Avenue
Suite C
Mountain View, CA 94043
(415) 940-1146
(415) 940-1634 Fax

CRI-MET
Recycle Facility, Braithwaite
LA 70040
Sales Office, 101 Merritt 7
Corporate Park
P.O. Box 5113
Norwalk, CT 06856-5113
(203) 854-2958

Cyprus Miami Mining
Highway 60
Claypool, AZ 85532
(602) 473-7100

The Doe Run Co.
Highway KK
Boss, MO 65440
Louis J. Magdits
(314) 626-3476

The Doe Run Co.
881 Main Street
Herculaneum, MO 63048
Anthony Worchester
(314) 933-3107

East Penn Mfg. Co., Inc.
Deka Road
Lyon Station, PA 19536
Dan Breidegam, Rick Leiby
(215) 682-6361

Encycle Texas, Inc.
5500 Up River Road
Corpus Christi, TX 78407
R.N. George, Jill Albert
(512) 289-0300
(800) 443-0144

Eticam - East Coast
410 South Main Street
Providence, RI 02903
(800) 541-8673
(401) 738-3261
(401) 738-1073 Fax

Eticam - West Coast
2095 Newlands Drive, East
Fernley, NV 89408
(800) 648-9963
(702) 575-2760
(702) 575-2803 Fax

Exide Corp.
P.O. Box 14205
Reading, PA 19612-4205
Robert Jordan
*800) 437-8495
2nd plant in Muncie, IN

GNB, Inc.
Box 2165, Joy Road
Columbus, GA 31902
Kenneth H. Strunk
(404) 689-1701

Gopher Smelting & Refining
3385 Highway 149
Eagan, MN 55121
Maier Kutoff
(612) 454-3310

Gulf Chemical and Metallurgical Corp.
302 Midway Road
P.O. Box 2290
Freeport, TX 77541
(409) 233-7882
(409) 233-7171

Horsehead Resource Development Company
613 Third Street
Palmerton, PA 18071
Jerry C. Odenwelder
(800) 253-5579
(610) 826-8835
(610) 926-8993 Fax
Plants in IL, PA, TN, and TX

Inorganic Service Corporation
4374 Tuller Road
Dublin, OH 43017
Alan B. Sarko
(614) 798-1890
(614) 798-1895 Fax

INMETCO - The International Metals Reclamation Co.
P.O. Box 720
245 Portersville Road
Ellwood City, PA 16117
John J. Liotta
(412) 758-5515
(412) 758-9311 Fax

Mercury Refining Company
790 Watervliet-Shaker Road
Latham NY 12009
Vicki Hart
(518) 785-1703

Noranda Minerals
Brunswick Mining & Smelting Corp. Ltd.
Belledune, New Brunswick
Canada E0B 1G0
P. Evans (506) 522-2100
K. McGuire (416) 982-7495

Nova Lead, Inc.
1200 Garnier
Ville Ste.-Catherine
Quebec, Canada J0L 1E0
Brian McIver
(514) 632-9910

NSSI/Sources and Services
P.O. Box 34042
Houston, TX 77234
(713) 641-0391

Parkans International
5521 Armour Drive
Houston, TX 77220
(713) 675-9141
(713) 675-4771 Fax

Pittsburgh Mineral and Environmental Technology
700 Fifth Avenue
New Brighton, PA 15066-1837
William F. Sutton
(412) 843-5000
(412) 843-5353 Fax

Quicksilver Products
200 Valley Drive, Suite #1
Brisbane, CA 94005
(415) 468-2000
(800) 275-2554

Refined Metals Corp.
257 W. Mallory
Memphis, TN 38109
Bill Freudiger
(901) 775-3770
2nd plant in Beech Grove, IN

Schuylkill Metals Corp.
Baton Rouge
Box 74040
Baton Rouge, LA 70874
Glen Krause
(800) 621-8236

Schuylkill Metals Corp.
Canon Hollow
P.O. Box 156
Forest City, MO 64451
Ken Fisher
(816) 446-3321

Seaview Thermal System
P.O. Box 3015
Blue Bell, PA 19422
Cheryl Camuso
(215) 654-9800

Vulcan Lead Resources
1400 W. Pierce
Milwaukee, WI 53204
Paul See
(800) 776-7152

Westinghouse Electric
Pittsburgh, PA
Robert J. Benke
(412) 642-3321
(412) 642-4985 Fax

Zia Technology of Texas
Burleson County Road 105
P.O. Box 690
Caldwell, TX 75240
(409) 567-7777

WASTE EXCHANGES

Waste exchanges are information clearinghouses with the goal of matching waste generators and waste users. The waste exchanges typically publish catalogs on a quarterly or bimonthly basis describing wastes available and desired. The catalogs contain brief descriptions of the type and quantity of material wanted or available. The listings typically are classified by waste type. In addition to the paper copy, many exchanges maintain an online computer database.

To ensure confidentially, listings are assigned a unique code number. The waste description in the catalog or online listing is associated with a code rather than a company name or phone number. All listings are identified by code but may be either confidential or nonconfidential. The exchange forwards any inquiries about confidential listings to the listing company. That company then chooses the respondents with whom it wishes to negotiate. To expedite inquiries about nonconfidential listings, the exchange will send a company name directly in response to requests about a waste listing.

North American Waste Exchanges

Alabama Waste Materials Exchange
Ms. Linda Quinn
404 Wilson Dam Avenue
Sheffield, AL 35660
(205) 760-4623

Alberta Waste Materials Exchange
Alberta Research Council
Ms. Cindy Jensen
6815 Eight Street North
Digital Building, 3rd Floor
Calgary, Alberta
Canada T2E 7H7
(403) 297-7505
(403) 340-7982 Fax

Arizona Waste Exchange
Mr. Barrie Herr
4725 East Sunrise Drive
Suite 215
Tucson, AZ 85718
(602) 299-7716
(602) 299-7716 Fax

Arkansas Industrial Development Council (b)
Mr. Ed Davis
#1 Capitol Hill
Little Rock, AR 72201
(510) 682-1370

B.A.R.T.E.R. Waste Exchange
Mr. Jamie Anderson
MPIRG
2512 Delaware Street, SE
Minneapolis, MN 55414
(612) 627-6811

Bourse Quebecoise des Matrieres Secondaires
Mr. Francois Lafortune
14 Place Du Commerce
Bureau 350
Le-Des-Squeurs, Quebec
Canada H3E 1T5
(514) 762-9012
(514) 873-6542

British Columbia Waste Exchange
Ms Jill Gillet
1525 West 8th Ave., Suite 102
Vancouver, BC,
Canada V6J 1T5
(604) 731-7222 - Gen. Info
(604) 734-7223 Fax

Bureau of Solid Waste Management (b)
Ms. Lynn Persson
P.O. Box 7921
Madison, WI 53707
(608) 276-3763

California Materials Exchange (CALMAX)
Ms. Joyce L. Mason
Integrated Waste Management Board
8800 Cal Center Drive
Sacramento, CA 95826
(916) 255-2369
(916) 255-2221 Fax

California Waste Exchange
Ms. Claudia Moore
Hazardous Waste Management Program
Department of Toxic Substances Control
P.O. Box 806
Sacramento, CA 95812-0806
(916) 322-4742

Canadian Chemical Exchange (a)
Mr. Philippe LaRoche
P.O. Box 1135
Ste-Adele, Quebec
Canada J0R 1L0
(514) 229-6511 or
(800) 561-6511
(514) 229-5344 Fax

Canadian Waste Materials Exchange
ORTECH International
Dr. Robert Laughlin
2395 Speakman Drive
Mississauga, Ontario
Canada L5K 1B3
(416) 822-4111, ext. 265
(416) 823-1446 Fax

Department of Environmental Protection (b)
Mr. Charles Peters
18 Riley Road
(502) 564-6761

Durham Region Waste Exchange
Mr. Elaine Collis
Region of Durham
Works Department
Box 603, 105 Conaumers Dr.
Whitby, Ontario
Canada L1N 8A3
(416) 668-7721
(416) 668-2051 Fax

Essex-Windsor Waste Exchange
Mr. Steve Stephenson
Essex-Windsor Waste
Management Committee
360 Fairview Avenue West
Essex, Ontario
Canada N8M 1Y6
(519) 776-6441
(519) 776-4455 Fax

Hawaii Materials Exchange
Mr. Jeff Stark
P.O. Box 1048
Paia, Hawaii 96779
(808) 579-9109
(808) 579-9109 Fax

Hudson Valley Materials Exchange
Ms. Jill Gruber
P.O. Box 550
New Paltz, NY 12561
(914) 255-3749
(914) 255-4084 Fax

Indiana Waste Exchange
Mr. Jim Britt
c/o Recyclers Trade Network, Inc.
P.O. Box 454
Carmel, IN 46032
(317) 574-6505 or
(317) 844-8764

Industrial Materials Exchange (IMEX)
Mr. Bill Lawrence
110 Prefontaine Place, South
Suite 210
Seattle, WA 98104
(206) 296-4899
(206) 296-3997 Fax

Industrial Materials Exchange Service
Ms. Diane Shockey
P.O. Box 19276, #34
Springfield, IL 62794-9276
(217) 782-0450
(217) 782-9142 Fax

Intercontinental Waste Exchange
Mr. Kenneth J. Jucker
5200 Town Center Circle
Suite 303
Boca Raton, FL 33486
(800) 541-0400
(407) 393-6164 Fax

Iowa Waste Reduction Center By-Product and Waste Search Service (BAWSS)
Ms. Susan Salterberg
University of Northern Iowa
Cedar Falls, IA 50614-0185
(800) 422-3109
(319) 273-2079
(319) 273-2893 Fax

Louisiana/Gulf Coast Waste Exchange
Ms. Rita Czek
1419 CEBA
Baton Rouge, OA 70803
(504) 388-8650
(504) 388-4945 Fax

Manitoba Waste Exchange
Mr. Todd Lohvinenko
c/o Recycling Council of Manitoba, Inc.
1812-330 Portage Ave.
Winnipeg, Manitoba
Canada R3C 0C4
(204) 942-7781
(204) 942-4207 Fax

MISSTAP
Ms. Caroline Hill
P.O. Drawer CN
Mississippi State, MS 39762
(601) 325-8454
(601) 325-2482 Fax

Missouri Environmental Improvement Authority (b)
Mr. Thomas Welch
325 Jefferson Street
Jefferson City, MO 65101
(314) 751-4919

Minnesota Technical Assistance Program (b)
Ms. Helen Addy
1313 Fifth Street, Suite 307
Minneapolis, MN 55414
(612) 627-4555

Montana Industrial Waste Exchange
Montana Chamber of Commerce
P.O. Box 1730
Helena, MT 59624
(406) 442-2405

New Hampshire Waste Exchange
Ms. Emily Hess
122 N. Main Street
Concord, NH 03301
(603) 224-5388
(603) 224-2872 Fax

New Jersey Industrial
Waste Information Exchange
Mr. William Payne
50 West State Street
Suite 1110
Trenton, NJ 08608
(609) 989-7888
(609) 989-9696 Fax

New Mexico Material Exchange
Mr. Dwight Long
Four Corners Recycling
P.O. Box 904
Farmington, NM 87499
(505) 325-2157
(505) 326-0015 Fax

New York City Department of Sanitation
Ms. Patty Tobin
44 Beaver Street, 6th Floor
New York, NY 10004

Northeast Industrial Waste Exchange, Inc.
Ms. Carrie Mauhs-Pugh
620 Erie Boulevard West
Suite 211
Syracuse, NY 13204-2442
(315) 422-6572
(315) 422-4005 Fax

Oklahoma Waste Exchange Program
Mr. Fenton Rude
P.O. box 53551
Oklahoma City, OK 73152
(405) 271-5338

Olmsted County Materials Exchange
Mr. Jack Stansfield
Olmsted County Public Works
2122 Campus Drive
Rochester, MN 55904
(507) 285-8231
(507) 287-2320 Fax

Ontario Waste Exchange
ORTECH International
Ms. Mary Jane Hanley
2395 Speakman Drive
Mississauga, Ontario
Canada L5K 1B3
(416) 822-4111, ext. 512
(416) 823-1446 Fax

Peel Regional Recycling Assistance
(Publishes Directory of Local Recyclers)
Mr. Glen Milbury
Regional Municipality of Peel
10 Peel Center Drive
Brampton, Ontario
Canada L6T 4B9
(416) 791-9400

PenCycle
Manager
PA Recycling Council
25 West Third Street
Media, PA 19063
(215) 892-9940
(215) 892-0504 Fax

Portland Chemical Consortium
Dr. Bruce Brown
P.O. Box 751
Portland, OR 97207-0751
(503) 725-4270
(503) 725-3888 Fax

RENEW
Ms. Hope Castillo
Texas Natural Resource
Conservation Commission
P.O. Box 13087
Austin, TX 78711-3087
(512) 463-7773

Review Materials Exchange
Mr. Adam Haecker
345 Cedar Street, Suite 800
St. Paul, MN 55101
(612) 222-2508
(612) 222-8212 Fax

Resource Exchange Services
Mr. Brendan Prebo or
Mr. Howard Hampton
213 East Saint Joseph
Lansing, MI 48933
(517) 371-7171
(517) 485-4488

Rhode Island Department of Environmental Management
Ms. Marya Carr
Brown University
P.O. Box 1943
Providence, RI 02912
(410) 863-2715

Rocky Mountain Materials Exchange
Mr. John Wright
812 South Vine Street
Denver, CO 80209
(303) 692-3009
(303) 744-2153 Fax

SEMREX
Ms. Anne Morse
171 West Third Street
Winona, MN 55987
(507) 457-6460

South Carolina Waste Exchange
Mr. Doug Woodson
155 Wilton Hill Road
Columbia, SC 29212
(803) 755-3325
(803) 755-3833 Fax

Southeast Waste Exchange
Ms. Maxie May
Urban Institute
UNCC Station
Charlotte, NC 28223
(704) 547-2307

Southern Waste Information Exchange
Mr. Eugene B. Jones
P.O. Box 960
Tallahassee, FL 32302
(800) 441-SWIX (7949)
(904) 644-5516
(904) 574-6704 Fax

Vermont Business Materials Exchange
Ms. Connie Leach Bisson or
Mr. Muriel Durgin
Post Office Box 630
Montpelier, VT 05601
(802) 223-3441
(802) 223-2345 Fax

Wastelink, Division of Tecon, Inc.
Ms. Mary E. Malotke
140 Wooster Pike
Milford, OH 45150
(513) 248-0012
(513) 248-1094 Fax

Waterloo Waste Exchange
Mr. Mike Birett
Region of Waterloo
925 Erb Street West
Waterloo, Ontario
Canada N2J 3Z4
(519) 883-5137
(519) 747-4944 Fax

(a) For profit waste information exchange
(b) Industrial materials exchange service distributors

OTHER SOURCES OF INFORMATION ON RECYLCING TECHNOLOGIES AND MARKETS

American Metals Market
P.O. Box 1085
Southeastern, PA 19398-1085

Publishes newspapers and books providing information on the metals market and traditional scrap and bulk metals recyclers.

California Waste Exchange
Department of Toxic
Substances Control
P.O. Box 806
Sacramento, CA 9812-0806

Directory of Industrial Recyclers - Classified listing of businesses in and around California providing recycling services for acids, antifreeze, catalysts, caustics, metal-working coolants, dry cleaning wastes, metals and metal salts, lead, mercury, precious metals, oils, oil filters, solvents, transformers, and miscellaneous and surplus supplies.

Citizen's Clearinghouse for Hazardous Wastes
P.O. Box 6806
Falls Church, VA 22040
(703) 237-2249

Fact Packs - News clippings and other information giving the grassroots view of hazardous waste topics, including information on recycling.

Lead Industries Association
295 Madison Ave.
New York, NY
(212) 578-4750

Lead Recycling Directory - 1992 - This directory gives information on the types of lead-bearing materials processed by 35 facilities in 15 states and Canada. Forms of lead range from near pure lead sheeting, through lead alloys and drosses, to firing-range soils and paint removal debris.

Minnesota Trade Office
Department of Trade and Economic Development
1000 Minnesota World Trade Center
30 East Seventh Street
St. Paul, MN 55101-4902
(612) 297-4222 or (800) 657-3858
(612) 296-3555 Fax

Minnesota Environmental Protection Industry - Classified directory for Minnesota companies providing a wide range of environmental services.

Texas Water Commission
Recycle Texas
P.O. Box 13087
Austin, TX 78711
(512) 463-7761

Recycle Texas - A Reuse, Recycling, and Products Directory - This comprehensive guide describes recyclers of industrial materials and suppliers of products with recycled content. Over 300 recycling companies are profiled. Directory of material accepted and RCRA waste code accepted allow identification of recyclers for a wide range of materials. Emphasis is on Texas vendors, but there are entries from all of North America.

U.S. Bureau of Mines
Washington, DC

MINES-DATA database -
system operator (202) 501-0406,
modem (202) 501-0373 (1,200 or 2,400 baud,
8 data bits, no parity, 1 stop bit)
This bulletin board system allows a user online access to Bureau of Mines reports on mining and mineral use, such as Mineral Industry Surveys.

U.S. Environmental Protection Agency
401 M Street, S.W.
Washington, DC

RCRA/Superfund/UST - (800) 424-9346
Hotline providing information on RCRA, Superfund, and underground storage tank regulations.

Solid Waste Information Clearinghouse -
(800) 677-9424
Hotline providing information on recycling of solid waste (mainly municipal wastes).

Toxic Substances Control Act Hotline -
(202) 554-1404
Hotline providing information on TSCA regulators.

VISITT - Vendor Information System for Innovative Treatment Technologies
VISITT Hotline (80) 245-4505 or (703) 883-8448
Document Number: EPA/542/R-93/001
VISITT is an IBM PC-compatible database of treatment technology vendors. The main focus is on waste treatment but a number of recycling systems are discussed.

F.6 REFERENCES

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APPENDIX G

SUMMARY OF EPA EVALUATION CRITERIA OF REMEDIAL TECHNOLOGIES FOR SOILS, SEDIMENTS, AND SLUDGES

The following table (Table G-1) summarizes remedial technologies applicable to metal-contaminated sites. Each technology is evaluated for six of the nine evaluation criteria developed by EPA: Long-term Effectiveness and Permanence; Reduction of Toxicity, Mobility, or Volume; Short-term Effectiveness; Implementability; Cost; and Protection of Human Health and the Environment. They are not, however, evaluated against compliance with ARARs, and State and community acceptance because they must be determined based on site-specific evaluations.

TABLE G-1. SUMMARY OF EPA EVALUATION CRITERIA OF REMEDIAL TECHNOLOGIES FOR SOILS, SEDIMENTS, AND SLUDGES (Adapted from U.S. EPA, 1991, EPA/540/2-91/014)

Remedial Technology	Protection of Human Health and the Environment[(a)]	Long-term Effectiveness and Permanence	Reduction of Toxicity, Mobility, or Volume	Short-Term Effectiveness	Implementability	Cost
No action	Threat is not mitigated.	Contaminants would continue to migrate offsite and downward through the subsurface soil. Ground-water monitoring would determine degree of contaminant leaching and provide a warning mechanism.	Does not reduce toxicity, mobility, or volume of contamination in the soil.	Remedial action not involved. Protection of workers, community, and environment during remediation activities is not a consideration. Minimal protection of public health from exposure to on-site surface soils.	No implementability considerations. Would not interfere with future remedial actions.	No capital costs. There will be costs associated with sampling and analysis.
Excavation and offsite disposal	This alternative involves moving the waste from one site to another. Can be protective if the waste is disposed of in a RCRA-permitted landfill.	Long-term effectiveness for the waste site is excellent because the waste is being removed; however, the contaminant has not been treated or removed from the waste.	Does not reduce toxicity or volume of contaminants in the soil. Mobility is reduced by placing contaminants in a permitted landfill.	Dust may be generated during excavation and handling activities. Respiratory protection, fugitive dust control procedures, and air monitoring may be required to protect workers and community. Depending on the volume, large amounts of traffic may be generated.	Technologies are demonstrated and commercially available. Land disposal restrictions may apply. Would not interfere with future remediation actions at the site. Uses standard construction equipment and labor.	Typically $300-$500/ton, or more.
Barriers/ containment (Sec. 4.2.1)	Can significantly reduce release rates, but not a permanent remedy. Frequently used in conjunction with a treatment technology (e.g., cap employed to cover S/S waste or to control groundwater flow during a pump-and-treat process).	Provides protection of public health from exposure to onsite soil contamination and controls offsite migrations of contaminants. Not considered a permanent remedy. Groundwater monitoring required to verify that no leaching of contaminants occurs at downgradient locations.	Does not reduce toxicity or volume of contamination at the site. Reduces downward and lateral mobility of contaminants and reduces offsite migration of contaminants due to wind erosion, surface water run-off, and leaching.	Dust may be generated during excavation and handling activities. Respiratory protection, fugitive dust control procedures, and air monitoring may be required to protect workers and community.	Readily implemented, except for horizontal barriers under in situ materials. Technologies are reliable and commercially available. Uses standard construction equipment and labor.	Generally less expensive than most forms of treatment.

(a) Technology compliance with ARARs, and State and community acceptance must be determined based on site-specific evaluation.

TABLE G-1. (continued)

Remedial Technology	Protection of Human Health and the Environment[(a)]	Long-Term Effectiveness and Permanence	Reduction of Toxicity, Mobility, or Volume	Short-Term Effectiveness	Implementability	Cost
Solidification/ stabilization (ex situ or in situ) (Sec. 4.2.2)	Potentially protective because it reduces the potential for release of the contaminant to water or air. However, contaminant is not removed.	Data on long-term effectiveness of S/S are limited. Contaminant is not removed from the waste.	Increases volume of contaminated soil (approximately 10 to 100%). Can reduce the mobility of many metals in the soil. Pretreatment such as reduction of Cr(VI) to Cr(III) or oxidation of arsenite to arsenate may be needed.	Dust may be generated during excavation and handling activities. Respiratory protection, fugitive dust control procedures, and air monitoring may be required to protect workers and community.	Widely implemented and reliable. Large staging area required. Many vendors, mobile systems available for processing excavated soil. Bench-scale testing usually recommended. Presence of interfering compounds such as organics may inhibit solidification process. Effective binder is difficult to formulate when many contaminant types are present.	Generally $50-$150/ton.
Vitrification (ex situ or in situ) (Sec. 4.2.3)	If successful, permanent remedy with good long-term effectiveness. Can simultaneously treat a wide variety of contaminants, both organic and inorganic.	If successful, yields inert product, with low leachability. Data on long-term effectiveness of vitrification are limited. Products have potential reuse options.	Metals are immobilized in vitrified solid. Volume reduction occurs. Volatile metals (e.g., arsenic oxide), which can be difficult to retain in vitrified solid requires pretreatment to convert to less volatile forms.	Dust may be generated during excavation and handling activities (ex situ only). Respiratory protection, fugitive dust control procedures, and air monitoring may be required to protect workers and community. Dust control, respiratory protection, and air monitoring usually warranted. Significant off-gas control issues.	Significant off-gas production. Volatile metals such as mercury and cadmium may exist in off-gas. Extensive pilot-scale testing required. Labor-intensive; requires highly skilled personnel and sophisticated facilities and instrumentation. Significant interferences and incompatibilities. Limited commercial availability. High energy intensive	High cost and energy intensive, usually > $500/ton. Probably economically practical for only a small portion of existing metal waste sites.

(a) Technology compliance with ARARs, and State and community acceptance must be determined based on site-specific evaluation.

TABLE G-1. (continued)

Remedial Technology	Protection of Human Health and the Environment[(a)]	Long-Term Effectiveness and Permanence	Reduction of Toxicity, Mobility, or Volume	Short-Term Effectiveness	Implementability	Cost
Physical separation (e.g., screening, gravity separation, or flotation) (Sec. 4.3.1.1)	Can be protective if separation process produces output stream with metal concentrations below health risk concerns and if metal concentrate is properly recycled or disposed. Typically additional treatment (e.g., leaching, S/S) is required to meet the cleanup goal with some fractions.	Excellent if high removal efficiencies are attained and if the metal concentrate is properly recycled or disposed.	Permanently reduces toxicity of soil by removing metals. Concentrations of metals into much smaller volumes is a requirement for a successful system.	Dust may be generated during excavation and handling activities. Dust control, respiratory protection, and air monitoring usually warranted.	Bench- and pilot-scale testing required to assess all implementability considerations. Large staging area required. High removal efficiencies may be difficult to achieve and/or result in complex process. Requires specialized (but not necessarily expensive) facilities and equipment.	Varies greatly, from $10 to several hundred dollars per ton, depending on the complexity of the process.
Pyrometallurgical treatment (Sec. 4.3.1.3)	Can be protective if it recovers metals from waste materials.	Very high if high removal efficiencies are attained. Enriched products can be reused or recycled.	Permanently removes majority of metals and effectively immobilizes remainder of metals in the slag or residue.	Dust due to excavation. Thermal air emissions require treatment.	Many commercial smelting facilities do not have permits for hazardous waste. Requires specialized facilities and highly trained labor. Significant off-gas and need for air emissions scrubbing.	Variable; depends on metal concentration, distance to processor, market for the metal, and the marketability of the form of the metal in the waste.

(a) Technology compliance with ARARs, and state and community acceptance must be determined based on site-specific evaluation.

TABLE G-1. (continued)

Remedial Technology	Protection of Human Health and the Environment[(a)]	Long-Term Effectiveness and Permanence	Reduction of Toxicity, Mobility, or Volume	Short-Term Effectiveness	Implementability	Cost
Soil washing (ex situ or in situ) (e.g., aqueous or chemical leaching) (Sec. 4.3.1.2 and 4.3.2.1)	Very protective if high removal efficiencies are attained. Requires subsequent treatment of washing fluid.	Excellent if high removal efficiencies are attained.	Permanently reduces toxicity of soil by removing metals. Concentrates contaminants into a much smaller volume. In order to reduce volume, process must provide a satisfactory method for treating washing fluids.	Dust may be generated during excavation and handling activities (note: applies only to ex situ processing). Respiratory protection, fugitive dust control procedures, and air monitoring may be required to protect workers and community.	Subject to a number of incompatibilities and interferences. Soils which are high in clay, silt, or fines have proven difficult to treat. Most extraction solutions are effective only for a narrow range of metals and matrix combination. Bench- and pilot-scale testing required to assess all implementability considerations. High removal efficiencies can be very difficult to achieve and/or result in complex process. Requires fairly simple facilities and equipment and unspecialized labor. Large staging area required.	Generally several hundred dollars per ton. Value of recovered metal may partially offset treatment costs if a suitable concentrate can be produced.
Electrokinetics (Sec. 4.3.2.2)	Contaminants can be permanently removed from waste.	Very permanent, in that metals are recovered and recycled.	Permanently reduces toxicity of soil by removing metals and concentrating them.	Air emissions can be a concern. Can release gasses at electrodes.	Bench- and pilot-scale testing required. High removal efficiencies difficult to achieve. Requires specialized facilities. Multimetal-contaminated sites pose complications. Applicable to clayey soils.	Relatively expensive. Limited data on full-scale projects.

(a) Technology compliance with ARARs, and state and community acceptance must be determined based on site-specific evaluation.

APPENDIX H

GUIDE TO INFORMATION SOURCES

H.1 Purpose

This section gives brief descriptions of several information sources that were selected for their relevance to planning and conducting a site remediation project. Subsection H.2 is a tabulation of essential references for metal-contaminated sites. EPA-produced online and PC-based databases are described in Subsections H.3 and H.4. Subsection H.5 is a brief description of two PC-based databases (ReOpt and Hazrisk) from non-EPA sources.

H.2 TABULATION OF ESSENTIAL REFERENCES FOR METAL-CONTAMINATED SITES

TABLE H-1. POLICY REFERENCES AND DESCRIPTIONS OF CONTENT

Policy Reference	Description
Corrective Action for Solid Waste Management Units at Hazardous Waste Management Facilities: Proposed Rule. 55 FR 30798, July 27, 1990	This is the proposed Subpart S rule that defines requirements for conducting remedial investigations and selecting and implementing remedies at RCRA sites.
Revised Interim Soil Lead Guidance for CERCLA Sites and RCRA Corrective Action Facilities: OSWER Directive 9355.4-12, July 14, 1994, 25 pp.	This interim directive establishes a streamlined approach for determining protective levels for lead in soil at CERCLA and RCRA sites. It recommends screening levels for lead in soil for residential land use (400 ppm); describes how to develop site-specific preliminary remediation goals; and, describes a plan for soil lead cleanup at sites that have multiple sources of lead.

TABLE H-2. TECHNICAL REFERENCES AND DESCRIPTIONS OF CONTENT

Technical Reference	Description
Guidance for Conducting Remedial Investigations and Feasibility Studies under CERCLA (U.S. EPA, 1988, EPA/540/G-89/004)	This document provides the user with an overall understanding of the remedial investigation/feasibility study (RI/FS) process.
RCRA Facility Investigations (RFI) Guidance, Volumes 1-4 (U.S. EPA, 1989, EPA 530/SW-89-031)	These documents recommend procedures for conducting an investigation and for gathering and interpreting the data from the investigation.
Guide for Conducting Treatability Studies Under CERCLA (U.S. EPA, 1992, EPA/540/R-92/071a)	This report describes the necessary studies that determine a technology's effectiveness in remediating a CERCLA site.
Guide for Conducting Treatability Studies Under CERCLA: Soil Washing (U.S. EPA, 1991, EPA/ 540/2-91/020A)	This document provides guidance for planning, implementing, and evaluating soil washing treatability tests to support the remedy evaluation process for CERCLA sites
Engineering Forum Issue: Considerations in Deciding to Treat Contaminated Unsaturated Soils In Situ (U.S. EPA, 1993, EPA/540/S-94/500)	This paper assists the user in deciding if in situ treatment of contaminated soil is a potentially feasible remedial alternative and to assist in the process of reviewing and screening in situ technologies.

TABLE H-2. (continued)

Technical Reference	Description
Summary of Treatment Technology Effectiveness for Contaminated Soil (U.S. EPA, 1989, EPA/540/2-89/053)	This report presents information on a number of treatment options that apply to excavated soils and explains the BDAT contaminant classifications.
Technology Screening Guide for Treatment of CERCLA Soils and Sludges (U.S. EPA, 1988, EPA/540/2-88/004)	This guide contains information on technologies that may be suitable for managing soil and sludge containing CERCLA waste.
Innovative Treatment Technologies: Annual Status Report (Fifth Edition) (U.S. EPA, 1993, EPA/542/R-93/003)	This report documents the status of innovative treatment technology use in the Superfund Program.
Guide to Treatment Technologies for Hazardous Wastes at Superfund Sites (U.S. EPA, 1989, EPA/540/2-89/052)	This guide addresses alternative technologies that can be used to treat wastes at Superfund sites.
The Superfund Innovative Technology Evaluation Program: Technology Profiles, Sixth Edition (U.S. EPA, 1993, EPA/540/R-93/526)	This document profiles 170 demonstration, emerging, and monitoring and measurement technologies being evaluated under the SITE Program.
Arsenic and Mercury – Workshop on Removal, Recovery, Treatment, and Disposal (U.S. EPA, 1992, EPA/600/R-92/105)	This document describes a broad range of issues and technologies related to arsenic and mercury recovery, treatment, and disposal.
A Review of Remediation Technologies Applicable to Mercury Contamination at Natural Gas Industry Sites (Gas Research Institute, 1993, GRI-93/0099)	This report describes remediation technologies that may have application for use at mercury-contaminated natural gas metering sites.
Selection of Control Technologies for Remediation of Lead Battery Recycling Sites (U.S. EPA, 1991, EPA/540/2-91/014)	This document provides information to facilitate the selection of treatment alternatives and cleanup services at lead battery recycling sites.
Contaminants and Remedial Actions at Wood Preserving Sites (U.S. EPA, 1992, EPA/600/R-92/182)	This document provides information that facilitates characterization of the site and selection of treatment technologies at wood preserving sites.
Engineering Bulletin: In Situ Soil Flushing (U.S. EPA, 1991, EPA/540/2-91/021)	This provides the latest information available on soil flushing technology and related issues.
Engineering Bulletin: Landfill Covers (U.S. EPA, 1993, EPA/540/S-93/500)	This provides the latest information on landfill covers and related issues.
Engineering Bulletin: Selection of Control Technologies for Remediation of Lead Battery Recycling Sites (U.S. EPA, 1992, EPA/540/S-92/011)	This provides the latest information on selected treatment technologies for remediation of lead battery recycling sites.
Engineering Bulletin: Solidification/Stabilization of Organics and Inorganics (U.S. EPA, 1993, EPA/540/S-92/015)	This provides the latest information on solidification/stabilization and related issues.
Engineering Bulletin: In Situ Vitrification Treatment (U.S.EPA, 1994, EPA/540/S-94/504)	This summarizes (8 pp.) in situ vitrification technology description, performance, status, and references.
Engineering Bulletin: Slurry Walls (U.S. EPA, 1992, EPA/540/S-92/008)	This summarizes the latest information available on slurry walls and related issues.
Engineering Bulletin: Technology Preselection Data Requirements (U.S. EPA, 1992, EPA/540/S-92/009)	This provides a listing of soil, water, and contaminant data elements needed to evaluate the potential applicability of technologies for treating contaminated soils and water.
Engineering Bulletin: Granular Activated Carbon Treatment (U.S. EPA, 1991, EPA/540/2-91/024)	This summarizes the latest information on granular activated carbon treatment and related issues.
Engineering Bulletin: Chemical Oxidation Treatment (U.S. EPA, 1991, EPA/540/2-91/025)	This provides the latest information available on chemical oxidation treatment and related issues.

TABLE H-2. (continued)

Technical Reference	Description
Engineering Bulletin: Soil Washing Treatment (U.S. EPA, 1990, EPA/540/2-90/017)	This provides the latest information available on soil washing treatment and related issues.
Handbook for Stabilization/Solidification of Hazardous Wastes (U.S. EPA, 1986, EPA/540/2-86/001)	This handbook provides remedial action plans for hazardous waste disposal sites with the information and general guidance necessary to judge the feasibility of stabilization/solidification technology for the control of pollutant migration from hazardous wastes disposed of on land.
Technical Resource Document: Solidification/ Stabilization and its Application to Waste Materials (U.S. EPA, 1993, EPA/530/R-93/012)	This document promotes the best future application of S/S processes.
Vitrification Technologies for Treatment of Hazardous and Radioactive Wastes (U.S. EPA, 1992, EPA/625/R-92/002)	This document presents applications and limitation of vitrification technologies for treating hazardous and radioactive wastes.
Handbook: Stabilization Technologies for RCRA Corrective Actions (U.S. EPA, 1991, EPA/625/6-91/026)	This document provides guidance on identification of the types of environmental settings that should be the focus of stabilization actions, on technical approaches to accelerate data gathering in support of decisions on appropriate stabilization measures, and on phasing the RCRA Facility Investigation process to gather the necessary data to make timely decisions within the frame work of the existing corrective action program.
Handbook on In Situ Treatment of Hazardous Waste Contaminated Soils (U.S. EPA, 1990, EPA/540/2-90/001)	This handbook provides state-of-the-art information on in situ technologies for use on contaminated soils.
Final Covers on Hazardous Waste Landfills and Surface Impoundments (U.S. EPA, 1989, EPA/530/SW-89/047)	This document recommends and describes a design for landfill covers that will meet the requirements of RCRA regulations
Lining of Waste Containment and Other Impoundment Facilities (U.S. EPA, 1988, EPA/600/2-88-052)	This report provides technological information on liner and cover systems for waste storage and disposal units with particular emphasis on polymeric flexible membrane liners.
Design, Construction, and Evaluation of Clay Liners for Waste Management Facilities (U.S. EPA, 1988, EPA/530/SW-86/007F)	This Technical Resource Document (TRD) is a compilation of available information on the design, construction, and evaluation of clay liners for waste landfills, surface impoundments, and wastepiles.
Technical Guidance Document: Inspection Techniques for the Fabrication of Geomembrane Field Seams (U.S. EPA, 1991, EPA/530/SW-91/0151)	This document is focused on all current methods of producing geomembrane seams including HDPE and VLDPE, PVC, PVC-R, CSPE, CSPE-R, CPE, EIA and EIA-R.
Technical Guidance Document: Construction Quality Management for Remedial Action and Remedial Design Waste Containment Systems (U.S. EPA, 1992, EPA/540/R-92/073)	This document reviews the significant physical properties associated with the construction materials used in waste containment designs and reviews the sampling and acceptance stategies required for Construction Quality Management.

TABLE H-3. TECHNICAL SUPPORT SERVICES AND DESCRIPTION OF CONTENT

Title	Description
Engineering Technical Support Center (ETSC) Contact: Ben Blaney (513) 569-7406	The ETSC provides quick-response technical assistance to Remedial Project Managers, on focused, site-specific problems on Superfund and RCRA sites through the use of technology teams from RREL.
Treatability Study Assistance Program (TSAP) Contact: Ben Blaney 513-569-7406	The TSAP consults on and conducts treatability studies for Regional Remedial Project Managers.
Superfund Technical Assistance Response Team (START) Contact: Ben Blaney (513) 569-7406	The START provides technical support on Superfund site remediation from the point of initial site evaluation through post-ROD design phases of remedial actions.
Environmental Monitoring Systems Laboratory, Las Vegas (EMSL-LV) Contact: Ken Brown (702) 798-2270	The EMSL-LV provides scientific and technical assistance in contaminant detection, hydrologic monitoring, site characterization, sample analysis, data interpretation, and geophysics. Services include X-ray fluorescence field survey methods and saturated and unsarurated zone monitoring.
Robert S. Kerr Environmental Research Laboratory (RSKERL) Contact: Don Draper (405) 332-8800	The RSKERL provides technical assistance such as evaluating remedial alternatives, reviewing RI/FS and RA/RD work plans, and providing technical information.
Environmental Response Team (ERT) Contact: Joseph Lafornara (908) 321-6740	The ERT, Edison, New Jersey provides support in responding to releases of hazardous waste, chemicals, and oil.
Environmental Research Laboratory, Athens (ERL-Athens) Contact: Dermont Bouchard (404) 546-3130	The ERL, Athens emphasizes multimedia exposure and risk assessment modeling (eg., MINTEQA2) of remedial action alternatives.

TABLE H-4. BIBLIOGRAPHIES AND DESCRIPTIONS OF CONTENT

Title	Description
The Federal Data Base Finder (Information USA, 1990)	A comprehensive listing of Federal databases and data files.
Technical Support Services for Superfund Site Remediation and RCRA Corrective Action (U.S. EPA, 1991, EPA/540/8-91/091)	Discussion of technical support services available to field staff.
Bibliography of Federal Reports and Publications Describing Alternative and Treatment Technologies for Corrective Action and Site Remediation (U.S. EPA, 1991, EPA/540/8-91/007)	Information for EPA remedial managers and contractors who are evaluating cleanup remedies.
Compendium of Superfund Program Publications (U.S. EPA, 1991, EPA/540/F-91/014)	A comprehensive catalog of documents on the Superfund program.
Catalogue of Hazardous and Solid Waste Publications (U.S. EPA, 1992, EPA/530-B-92-001)	A selected list of documents produced by EPA's Office of Solid Waste (OSW) on hazardous and solid wastes.
Bibliography of Articles from Commercial Online Databases Describing Alternative and Innovative Technologies for Corrective Action and Site Remediation (U.S. EPA, 1991)	Compiled by EPA's Hazardous Waste Superfund Collection for use by EPA remedial managers and contractors who are evaluating cleanup options.
Bibliography of Articles from the NTIS Database Describing Alternative and Innovative Technologies for Corrective Action and Site Remediation (U.S. EPA, 1991)	Compiled by EPA Library's Hazardous Waste Superfund Collection for use by EPA remedial managers and contractors who are evaluating cleanup options.
Superfund Information Access Series (U.S. EPA, 1993. EPA/220-B-91-027 - EPA/220-B-92-033)	A series of handbooks prepared by EPA Library's Hazardous Waste Superfund Collection to provide information to assist EPA staff and promote technology transfer. Covers various categories of publications and databases.

H.3 ONLINE (DIAL-UP) DATABASES

The databases described in this section can be accessed via modem. Most are bibliographic in nature and have some messaging or bulletin board system (BBS) capabilities. Information needed to access these databases is provided. Most can be used free of charge, except for telecommunications costs. Several have toll-free (800) numbers or Internet access codes, which essentially eliminate the telecommunication cost.

H.3.1 Alternative Treatment Technology Information Center (ATTIC)

The ATTIC network is maintained by the Technical Support Branch of EPA's Risk Reduction Engineering Laboratory (RREL). ATTIC includes: databases (e.g., Treatment Technology Database, RREL Treatability Database, The Underground Storage Tank (UST) abstracts database (available in Fall 1994); full text documents (e.g., EPA Engineering Bulletins); and a calendar of events that contains as extensive list of conferences, seminars, and workshops on treatment of hazardous waste.

The **Technical Assistance Directory** lists experts from government, universities, and consulting firms who can provide guidance on technical issues or policy questions.

There is no charge for the ATTIC service. It is available via modem over standard telephone lines. The phone number for the ATTIC modem contact is (703) 908-2138 (1200 or 2400 baud) and the modem settings are no parity, 8 data bits, 1 stop bit, and full duplex. For more information on ATTIC, call Dan Sullivan, EPA, (908) 321-6677 or FAX (908) 906-6990.

Alternative Treatment Technology Information Center (ATTIC): User's Manual, Version 1.0. Prepared by the U.S. EPA Risk Reduction Engineering Laboratory, Technical Support Branch. EPA/600/R-92/130.

H.3.2 Clean-Up Information Bulletin Board System (CLU-IN)

CLU-IN is run by the Technology Innovation Office, which is part of EPA OSWER. Its scope is hazardous waste cleanup technologies and activities. It provides an online messaging and BBS and several Special Interest Groups (SIGs) to facilitate communication and information sharing. There are also a number of bulletins that can be searched and downloaded. They include certain publications prepared by the Hazardous Waste Superfund Collection, abstracts of *Federal Register* notices on hazardous waste, information on training programs, and directories of EPA contacts for questions related to hazardous waste cleanup.

Access to CLU-IN is available to the public, and a user ID can be obtained simply by dialing up and registering. However, access to a few special interest groups is restricted to EPA employees. The dial-in number is (301) 589-8366 (1200/2400/9600 baud), and the modem settings are 8 data bits, 1 stop bit, no parity, and full duplex.

CLU-IN: Cleanup Information Electronic Bulletin Board – User's Guide. Can be obtained by calling the system operator at (301) 589-8368 or sending an online message to the designation topic "SYSOP."

H.3.3 Comprehensive Environmental Response, Compensation, and Liability Information System (CERCLIS)

The CERCLIS database provides access to information on more than 37,000 waste sites from their initial identification as potentially hazardous to being listed on the National Priorities List. Data provided for each site include location, classification, assessment data, remedial information, and points of contact. CERCLIS is sponsored by EPA's Office of Emergency and Remedial Response.

The CERCLIS database is maintained on EPA's central computing system, the National Computer Center (NCC), in Research Triangle Park, North Carolina. Employees of EPA, other Federal agencies, State agencies, and contractors working on EPA projects first must obtain an NCC user ID and then register for the CERCLIS database by contacting the CERCLIS staff at (703) 603-9091. Others may call the CERCLIS Hotline at (703) 538-7234 to request a search of the database.

H.3.4 EPA Online Library System (OLS)

The EPA library network maintains EPA OLS, which contains bibliographic citations to EPA reports as well as book and articles. These citations are received from NTIS and the Regional EPA libraries. OLS has several databases, of which the most applicable for readers of this document are described below. Records can be searched by title, authors, corporate sources, keywords, year of publication, and EPA, NTIS, or other report number.

The **National Catalog** contains bibliographic data and holdings information on EPA reports listed in the NTIS database and the National Catalog.

The **Hazardous Waste Superfund Data Collection** contains bibliographic citations to hazardous waste materials that are available in the Hazardous Waste Superfund Collection at EPA's Headquarters Library. (Note: HWSDC is also available on diskette; see following section on PC-based products.)

The **Chemical Collection System** has citations to copies of articles in the Office of Toxicological Substances (OTS) Chemical Collection System.

OLS resides on the mainframe at EPA's National Computer Center. Access is available through the Federal BBS, (202) 512-1387; via Internet (EPAIBM.RTPNC.EPA.GOV – Public Access OLSA); or through the Library Online System, (919) 549-0720, 9600 baud, and the modem settings are 7 data bits, 1 stop bit, even parity, and half duplex.

Public Access to EPA's Online Library System (OLS) and *Public Access Online Library System (OLS)*, EPA 220-F-92-006 and EPA 220-B-92-017, respectively, can be obtained by calling the Public Information Center at (202) 260-2080.

H.3.5 Integrated Risk Information System (IRIS)

IRIS contains health risk and EPA regulatory information on more than 500 chemicals, along with more than 600 risk summaries. It summarizes chemical hazard identification and dose-response assessment, and presents EPA's consensus opinion on human health hazards associated with the referenced chemicals. In addition to bibliographic citations, IRIS contains data on and EPA scientific points of contact for oral and inhalation dose reference concentrations for noncarcinogenic effects and risk factors for chronic exposure to carcinogens.

IRIS is also available to EPA staff on diskette and then can be updated online through the EPA mainframe. Public access to IRIS is through the National Library of Medicine's Toxicology Network (TOXNET) or NTIS.

For more information, contact the IRIS User Support Unit at (513) 569-7254.

H.3.6 Center for Exposure Assessment Modeling (CEAM)

CEAM has implemented an electronic bulletin board for CEAM-supported models. The CEAM bulletin board serves four main purposes.

1. The downloading of CEAM-supported models
2. The uploading of user input datasets for staff review and troubleshooting assistance
3. The dissemination of current information concerning CEAM software, activities,a nd events (this includes announcements for CEAM workshops and training sessions, model version and update information, helpful hints for model use, and model documentation)
4. The ability to exchange information quickly between users and CEAM personnel concerning model use, problems, and enhancements.

The number to call for more information is (706) 546-3549. The phone number for dial-up access is (706) 546-3402. Modem settings are no parity, 8 data bits, and 1 stop bit.

H.3.7 Resource Conservation and Recovery Information System (RCRIS)

RCRIS contains information on facilities that handle hazardous waste and corrective-action information that supports the permit-writing and enforcement activities of the corrective-action program. The information contained in RCRIS is collected by the EPA Regional Offices and the states from permit applications, notification forms, and inspection reports.

The RCRIS database is maintained on EPA's central computing system, the National Computer Center (NCC), in Research Triangle Park. Employees of EPA, other federal agencies, state agencies, and contractors working on EPA projects first must obtain an NCC user ID and then register for the RCRIS database by contacting Patricia Murray at (202) 260-4697.

H.3.8 RODs Database

The RODs database contains the full text of all Superfund Records of Decision (RODs) that have been signed and published. It is sponsored by the EPA's Office of Emergency and Remedial Response. (Note: CERCLIS contains abstracts of all RODs prepared, whether or not they have been signed and published.) RODs can be searched by various indexed fields as well as by strings of words in the abstract and the full text of the Records of Decision. Indexed fields include site location, contaminated media, key contaminants, and selected remedy.

The RODs database is maintained on EPA's central computing system, the National Computer Center (NCC), in Research Triangle Park. Employees of EPA, other federal agencies, state agencies, and contractors working on EPA projects first must obtain an NCC user ID and then register for the RODs database by contacting the RODs staff at (703) 603-9091. Others may call the CERCLIS Hotline at (703) 538-7234 to request a search of the RODs database.

Records of Decision System: The Training Manual – Published in 1990, this document can be obtained by calling the RODs staff at the number given above.

Superfund Automated Records of Decision System (RODs): User Manual – Published in 1988 as EPA/540/G-89/005, this can be purchased through NTIS. The NTIS number is PB90-193004.

H.3.9 Subsurface Remediation Technology (SRT) Database

The SRT Database is a program designed to provide site-specific information concerning subsurface contamination and remediation activities presently being conducted or proposed at Superfund sites throughout the United States. The purpose of the database is to provide a single comprehensive source of information that can be shared and compared to other sites having similar problems or scenarios. The SRT Database consists of five related components: site characterization, methods of remediation, contaminants, consulting firms, and references cited.

The SRT Database allows searching for more than 60 contaminants that are most frequently found at hazardous waste sites. These represent contaminant classes, including metals, pesticides, chlorinated solvents, polycyclic aromatic hydrocarbons (PAHs), hydrocarbons and derivatives, and a general class composed of such contaminants as cyanide, pentachlorophenol, and vinyl chloride.

The SRT Database also allows searching based on the type or types of remediation technology being applied at a site. The technologies included range from the passive, such as barriers, drains, and covers, to the active, such as pump and treat, in situ biological, and soil vacuum extraction.

The SRT Database will be accessible through an online BBS located at the R.S. Kerr Environmental Research Laboratory in Ada, Oklahoma. The BBS should be in place approximately June, 1994. Contact Dr. David S. Burden, (405) 436-8606, for further information.

H.3.10 U.S. Bureau of Mines Database

The U.S. Bureau of Mines produces a wide range of documents on metals processing and economics. The latest information is available through the MINES FaxBack Document-on-Demand System. MINES FaxBack is a simple to operate automated fax response system, a service provided to facilitate rapid dissemination of publications produced by the U.S. Bureau of Mines. MINES FaxBack can be used to order documents to be delivered to your fax machine in minutes, 24 hours a day, 7 days a week by dialing (412) 892-4088 from a touch-tone telephone attached to a fax machine. Using MINES FaxBack, callers can retrieve the Bureau's monthly and quarterly Mineral Industry Surveys as soon as they are ready for printing, 2 to 3 weeks before the date of their public distribution. Comments or suggestions regarding the MINES FaxBack system can be faxed to (202) 501-3751. To learn more *about the technology behind FaxBack, request document #999 from* MINES FaxBack.

H.3.11 Air Model Clearinghouse Bulletin Board

This is an information exchange providing updates on regional air quality regulations and updates on air model status. ·For on-line access dial (919) 541-5742 with modem setting no parity, 8 data bits, and 1 stop bit. Baud rates of 1,200 to 14,400 are supported.

H.3.12 Pollution Prevention Information Exchange System (PIES)

PIES is a bulletin board system that links to several databases and provides messaging capabilities and forums on various topics related to pollution prevention. Through its link to the United Nation's International Cleaner Production Information Clearinghouse, it provides a communication link with international users. PIES is part of the Pollution Prevention Information Center (PPIC), which is supported by EPA's Office of Environmental Engineering and Technology Demonstration and Office of Pollution Prevention and Toxics.

PIES contains information about current events and recent publications relating to pollution prevention. Summaries of Federal, State, and corporate pollution prevention programs are provided. The two sections of the database cover case studies and general publications and can be searched by keywords related to specific contaminants, pollution prevention technologies, or industries.

The phone number for dial-up access is (703) 506-1025; qualified state and local officials can obtain a toll-free number by calling PPIC at (703) 821-4800. Modem settings are 2400 baud, no parity, 8 data bits, 1 stop bit, and full duplex.

H.4 PC-BASED DATABASES PRODUCED BY EPA

H.4.1 Cost of Remedial Action (CORA)

CORA was developed by the EPA to guide technology screening and assist in remedial action costing for Superfund sites. It also can be used for RCRA corrective actions. CORA has two separate modules.

The **expert system** is used for technology screening. It guides the user through technology by means of a series of questions, mostly of the yes/no and true/false type, and allows the user to enter site information of the type that is usually available at the remedial investigation stage. It then recommends remedial actions from a range of technologies.

The **cost system** is the better known of the CORA modules and is one of the most widely used cost estimating programs for remediation projects. Users can enter available information about a site, such as extent of contamination, types of contaminants, and the contaminated matrix. This information is then used by CORA to calculate the cost of remediation.

CORA is MS-DOS compatible. It is available at no cost to EPA offices, and can be purchased by others. Contact Jaya Zieman of CH2M Hill at (703) 478-3566.

H.4.2 Hazardous Waste Superfund Data Collection (HWSDC)

The content of this database is described in a previous paragaraph under dial-in databases. The PC version is available at EPA's Headquarters Library and at a few Region libraries. For information about obtaining the PC version, call Felice Sacks at (202) 260-3121.

H.4.3 Integrated Risk Information System (IRIS)

This database is described above, in the section on dial-in databases. For information about the PC-based version, contact the IRIS User Support Unit at (513) 569-7254.

H.4.4 RREL Treatability Database

This database is produced by the Risk Reduction Engineering Laboratory (RREL) within EPA's Office of Research and Development. The purpose of the database is to provide information on the removal and destruction of chemicals in such media as soil, water, sludge, sediment, and debris. It provides physical/chemical properties for each chemical along with treatability data. The types of treatment available for a specific compound are given, along with the type of waste treated, the size of the study/plant, and the treatment levels achieved.

As mentioned above, the RREL Treatability Database is available online through ATTIC. The PC version is distributed to a wide range of users at no cost. Requests for copies of the database should be addressed to: Glenn M. Shaul, Water and Hazardous Waste Treatment Research Division, EPA/RREL, 26 West Martin Luther King Drive, Cincinnati, OH, 45268. Requests can be faxed to Mr. Shaul at (513) 569-7787 [voice number (513) 569-7589].

H.4.5 Vendor Information System for Innovative Treatment Technologies (VISITT)

VISITT was assembled by the EPA OSWER to provide current information on innovative treatment technologies. Users of VISITT can screen innovative technologies for engineering feasibility and identify vendors who provide treatability studies and cleanup services for candidate technologies.

VISITT can be searched by waste, technology, vendor, or site. Within each category, a submenu allows identification of specific parameters that can be used to refine the search.

Information on VISITT availability and updates can be obtained by calling the VISITT Hotline at (800) 245-4505 or (703) 883-8448.

H.5 PC-BASED DATABASES FROM NON-EPA SOURCES

H.5.1 REOPT/RAAS Databases

ReOpt is a stand-alone PC database developed for the U.S. Department of Energy (DOE) at the Pacific Northwest Laboratory (PNL) as a part of the Remedial Action Assessment System (RAAS). DOE intends that RAAS will become a full-scale expert system on hazardous and radioactive waste remediation. Currently, RAAS exists in prototype form that is being beta-tested and refined. When complete, RAAS will serve as a computerized guide to the complete RI/FS process.

ReOpt, which is available both commercially from Sierra Geophysics and under government license from PNL, is a subset of RAAS that contains information about technologies that potentially could be used for cleanup at DOE or other waste sites, auxiliary information about possible hazardous or radioactive contaminants at such sites, and the Federal regulations that govern disposal of wastes containing these contaminants. The ReOpt user can view information on the screen, print specific information about a particular technology, or print complete ReOpt technology information for reference use.

ReOpt is a self-contained software package that requires no additional software to run. It is available for both Apple Macintosh (Macintosh II series running System 6.0 or higher, with a minimum of 5 MB of RAM, 12 MB disk storage, and a 13" color monitor) and IBM-compatible computers (386 series or higher running Microsoft Windows, minimum of 4 MB RAM, 12 MB of disk storage, and a VGA monitor). The government licensing agreement specifies that ReOpt may be used only for government projects – a contract number must be filed with PNL for each copy received. For industrial projects, the commercial version of ReOpt must be purchased from Sierra Geophysics, Inc.

H.5.2 HAZRISK Models

The HAZRISK Models are a commercially available PC-based database system for generating cost estimates and project cleanup schedules and identifying possible risks and contingencies. The models apply statistical analysis of actual cost data for completed projects. For more information, contact Jennifer Painter, Independent Project Analysis, Inc., at (703) 709-0777.

APPENDIX I

REMEDIATION TECHNOLOGY COSTS ESTIMATED BY THE CORA MODEL

The Cost of Remedial Options (CORA) computer code contains an expert system to evaluate technical feasibility of remedial options and a cost estimation module. The types of metal site remediation technologies included and the required input data are summarized in this appendix. Also, example estimates for four technologies are presented to indicate the application of CORA for cost estimating.

The cost model will prepare budget cost estimates for capital and first year operations and maintenance costs. The model is intended for preliminary cost estimates to identify major cost elements and allow comparison of technologies on a consistent basis. The detail and accuracy is not sufficient for feasibility study cost estimates.

CORA is an MS-DOS compatible program, available at no cost to EPA offices and can be purchased by others. For more information, call the CORA Hotline (703) 478-3566.

CORA VERSION 3.0
COST MODULE INPUT PARAMETERS (METALS REMEDIATION TECHNOLOGIES)

Region _______ Site Name ____________________________ Operable Unit ____________________________

Scenario ____________________________ Year of Start (FY) _________ EPA Contact ____________________

Cost Module		Input Parameters
101	Soil Cap	Site area (AC) .25-100 _____, Soil type (1-4) 1. gravel; 2. topsoil; 3. loam; 4. clay _____, Soil leveling layer thickness (ft) 0-1 _____, Soil protective layer thickness (ft) 0-1 _____, Topsoil layer thickness (ft) 0-2 _____, Level of protection (A,B,C,D,N) _____, Avg. temp. (F) _____, Level of confidence (H,M,L) _____
102	Asphalt Cap	Site area (AC) .25-100 _____, Soil leveling layer thickness (ft) .5-1 _____, Level of protection (A,B,C,D,N) _____, Avg. temp. (F) _____, Level of confidence (H,M,L) _____
103	Multilayered RCRA Cap	Site Area (AC) .25-100 _____, Soil type (1-4) 1. gravel; 2. topsoil; 3. loam; 4. clay _____, Soil leveling layer thickness (ft) 0-1 (Def 1) _____, Clay barrier thickness (ft) 2-4 (Def 2) _____, Synthetic membrane thickness (mils) 0-80 (Def 60) _____, Drainage layer thickness (ft) 1-2 (Def 1) _____, Filter fabric thickness (oz) 4, 6, 8 or 10 _____, Soil protection layer thickness (ft) .5-3.5 (Def 5) _____, Topsoil layer thickness (ft) .5-2 (Def 2) _____, Above membrane protection (A,B,C,D,N) _____, Below membrane protection (A,B,C,D,N) _____, Avg. temp. (F) _____, Level of confidence (H,M,L) _____
104	Soil-Bentonite Slurry Wall	Slurry trench length (ft) 100-9,000 _____, width (ft) 2-4 _____, depth (ft) 1-115 _____, Excavating conditions [easy (E), difficult (D)] _____, Key wall into bedrock? (Y,N) _____, % Contaminated soil (0-100) _____, % Unsuitable soil (0-100) _____, Miles to bentonite mix site _____, Miles to disposal area _____, Distance from Wyoming (MI) _____, % Bentonite for slurry (5-100) _____, % Slurry loss (10-100) _____, Level of protection (A,B,C,D,N) _____, Avg. temp. (F) _____, Level of confidence (H,M,L) _____
105	Surface Water Diversion	Site type (1-3) 1. Raised ground above floodplain; 2. Base of hill, above floodplain; 3. In floodplain _____, Avg. site length (ft) 1-9,999 _____, Collection avg site width (ft) 1-9,999 _____, If type 3: 25-yr, 24-hr storm (in) 0-12 _____, Avg. temp. (F) _____, Level of protection (A,B,C,D,N) _____, Level of confidence (H,M,L) _____

Cost Module		Input Parameters
201	Soil Excavation	Soil type (1-4) 1. gravel; 2. topsoil; 3. loam; 4. clay, Excavation depth (ft) max 25 _____, If depth >5' pick 1. steel sheet or 2. side slope _____, For each excavation, excavation length at max depth (ft) _____, Width at max depth (ft) _____, Cover depth above contaminated materials (ft) _____, In this operable contaminated excavation depth, continuous sampling (ft) _____, Sampling lift thickness (in) 6, 12, or 24 _____, If drums present: (unit) number of drums _____ or % contaminated zone occupied by drums _____, Base air monitoring? (Y/N) _____, Avg. temp. (F) _____, Protection level (A,B,C,D,N) - uncontaminated materials _____, contaminated materials _____, Level of confidence (H,M,L) _____
202	Sediment Excavation and Dredging	Avg. excavation length (ft) _____, width (ft) _____, depth (ft) 1-15 _____, Excavation side slope ratio (X:1) 0-9 _____, Materials submerged? (Y/N) _____, Submerged depth (ft) _____, % Solids in sediment (1-50) _____, Sediment contain a lot of oil/non-dissolved organics (Y/N) _____, If yes, % organics by volume _____, Avg. temp. (F) _____, Level of protection (A,B,C,D,N) _____, Level of confidence (H,M,L) _____
203	Pumping Contained Wastes	Gallons water between .01% and 7% solids _____, Conc. of solids in this range (%) _____, Volume organics (gal) _____, gal. sludge between >7% and 20% solids _____, Conc. of solids in this range (%) _____, Onsite treatment feasible (Y/N) _____, Treat sludge to 50% solids? (Y/N) _____, Following tests required (Y/N): water cation _____, water organic _____, water anion _____, general water _____ organic phase _____, sludge phase _____, Vol. batches to analyze (gal) _____, Level of protection (A,B,C,D,N) _____, Avg. temp. (F) _____, Level of confidence (H,M,L) _____
204	Drum Removal	No. of drums ready for transport _____, No. of drums requiring: removing/staging (10 or greater) _____, Overpacks _____, Consolidation _____, Waste compatibility characterization _____, Avg. % for all drums _____, Level of protection (A,B,C,D,N) _____, Avg. temp. (F) _____, Level of confidence (H,M,L) _____
206	Groundwater Extraction	No. of wells known? (Y/N) _____, Depth to top of target vol (ft) (1-2,000) _____, Width of target vol. (ft) (1-999,999) _____, Length of target vol. (ft)(1-999,999) _____, Thickness of target volume (ft) (1-500) _____, Porosity of aquifer (0.01-0.5) _____, Aquifer transmissivity (ft^2/day) (10-1,000,000) _____, Aquifer thickness (ft) (10-2,000) _____, Depth to top of aquifer (ft) _____, Depth to static GW level (ft) _____, Hydraulic gradient (0.0-0.1) _____, GW recharge into target volume (in/yr)(0-100) _____ (if unknown, assume 20% of annual avg. precipitation), Aquifer flushing factor (0.01-1.0) _____, Min. well spacing allowable (ft) (5-9,999) _____, Primary contaminant name _____, Initial concentration (ug/l) _____, Target concentration (ug/l) _____, Dist. coefficient [kd] (ml/g) _____, Time to clean (yrs) (0-100,000) _____, If full containment is desired, enter 0, Bulk Density (g/cm^3)(1.6-2.1) _____, Will wells be gravel-packed (Y/N) _____, Length of transfer piping (ft) _____, Avg. temp. (F) _____, Level of confidence (H,M,L) _____, Protection during active drilling operations (A,B,C,D,N) _____, During setup of drill rig and installation above-grade piping (A,B,C,D,N) _____

Cost Module		Input Parameters
303	Soil Flushing	Flush area length (ft) _____, width (ft) _____, Municipal water available within 100 feet? (Y/N) _____, Avg. temp. (F) _____, Level of protection (A,B,C,D,N) _____, Level of confidence (H,M,L) _____
311	Metals Precipitation	Flow (gpm) 20-1,000 _____, pH (1-14) _____, Adjust pH with lime or caustic (L/C) _____, Avg. temp. (F) _____, Level of confidence (H,M,L) _____, Level of protection (A,B,C,D,N) _____, Concentrations (mg/l)--TSS (50-1,000) _____, *Acidity (0-1,000) _____, *Alkalinity (0-1,000) _____, Cd (.1-10) _____, Zn (.5-500) _____, Ni (.5-100) _____, Pb (.5-5) _____, Cu (.5-75) _____, Hg (.01-10) _____, Cr6 (.5-50) _____, Cr3 (.5-50) _____, Ba (1-5) _____, Al (1-1,000) _____, Ca (1-1,000) _____, Fe (1-10,000) _____, Mg (1-50) _____, Mn (1-500) _____, SO4 (10-10,000) _____. *If unknown, see Scope Definition Section of Users Manual for estimating procedure.
312	Ion Exchange	Flow (gpm) 50-600 _____, Level of protection (A,B,C,D,N) _____, Avg. temp. (F) _____, Level of confidence (H,M,L) _____, Concentrations (mg/l)--Cd _____, Zn _____, Ni _____, Pb _____, Cu _____. NOTE: If ion exchange follows metals precipitation system, metals concentrations to ion exchange can be estimated from solubilities at pH 10 shown in the metals precipitation fact sheet.
313	Pressure Filtration	Flow (gpm) 30-1,000 _____, TSS (mg/l) 5-50 _____, Level of protection (A,B,C,D,N) _____, Avg. temp. (F) _____, Level of confidence (H,M,L) _____
315	Offsite RCRA Treatment	RCRA treatment--Metals and/or cyanides waste vol. (drums or gal) _____; Metals only waste vol. _____; Miles to facility _____; Recycling and recycling volume (drums or gal) _____; Cost per gal or drum ($)--neg. no. is recyc. credit _____; Miles to facility _____, Level of confidence (H,M,L) _____, Cost for offsite treatment a capital or O&M cost (C or O)? _____, Cost for transportation a capital or O&M cost (C or O)? _____
316	Solidification	Waste volume (cy) _____, Unit weight of waste (pcf) 80-110 _____, Agent/waste proportion (tons agent/tons waste) 1-3 _____, % by weight of: Flyash (0-90) _____, Cement kiln dust (0-90) _____, Portland cement (0-100) _____, Hydrated lime (0-20) _____, Level of protection (A,B,C,D,N) _____, Avg. temp. (F) _____, Level of confidence (H,M,L) _____
317	In Situ Stabilization	Volume to be solidified (cy)(500-200,000) _____, Proportion stabilizing agent to contaminated material (tons agent/tons waste) (1-3), Total unit weight of waste (lb/ft^3)(8-110 solids/63-80 liquids), Stabilizing formulation; Flyash (wt %) (0-90) _____, Cement kiln dust (wt %)(0-90) _____, Portland cement (wt %)(0-100) _____, Hydrated lime (wt %)(0-20) _____; Site conditions: easy, moderate, difficult (E,M,D) _____; Level of protection (A,B,C,D,N) _____, Avg. temp. (F) _____, Level of confidence (H,M,L)

Cost Module		Input Parameters
401	Offsite RCRA Landfill	Volume of waste containing metals and organics (drums or cy) _____, Volume of waste containing PCBs (<500 ppm) _____, Miles to facility _____, Level of confidence (H,M,L) _____, Is landfill cost a capital or O&M cost (C or O)? _____, Is transportation cost a capital or O&M cost (C or O)? _____
402	Onsite RCRA Landfill (above grade)	Contaminated material (cy) 7,000-220,000 _____, Avg. annual rainfall (in) 0-100 _____, 25-Yr, 24-hr rainfall (in) 0-12 _____, Time to treat above grade stormwater (hrs) 8-120 _____, Level of protection (A,B,C,D,N) for: Cell construction _____, Filling and cap placement _____, Avg. temp. (F) _____, Level of confidence (H,M,L) _____
403	Onsite RCRA Landfill (below grade)	Contaminated material (cy) 7,000-220,000 _____, Avg. annual rainfall (in) 0-100 _____, 25-Yr, 24-hr rainfall (in) 0-12 _____, Time to treat above grade stormwater (hrs) 8-120 _____, Level of protection (A,B,C,D,N) for: Cell construction _____, Filling and cap placement _____, Avg. temp. (F) _____, Level of confidence (H,M,L) _____
404	Offsite Solid Waste Landfill	Waste volume (cy) _____, Landfill cost ($/cy) _____, Miles to facility _____, Avg. demurrage time period (hrs) _____, Level of confidence (H,M,L) _____, Is landfill cost a capital or O&M cost (C or O)? _____, Is transportation cost a capital or O&M cost (C or O)? _____
405	Discharge to POTW	Will the transmission be gravity flow or pressure (G or P)? _____, Flow (gpm) 20-2,000 _____, Pipe length (ft) 20-999,999 _____, Avg. trench depth (ft) 6-15 for gravity; 4-8 for pressure _____, Sewer use fee ($/1,000 gal) .42-1.78 _____, Avg. temp. (F) _____, Level of protection (A,B,C,D,N) _____, Level of confidence (H,M,L) _____
406	Discharge to Surface Water	Will the transmission be gravity flow or pressure (G or P)? _____, Flow (gpm) 20-2,000, Pipe length (ft) 1-999,999 _____, Avg. trench depth (ft) 6-15 for gravity; 4-8 for pressure _____, Diffuser required? (gravity only) (Y/N) _____, NPDES permit cost _____, Avg. temp. (F) _____, Level of protection (A,B,C,D,N) _____, Level of confidence (H,M,L) _____
407	Water Reinjection	Number of wells _____, Avg. well depth (ft) _____, Longest site dimension (ft) _____, Groundwater extraction rate (gpm) _____, Level of protection (A,B,C,D,N) above grade _____; below grade, Avg. temp. (F) _____, Level of confidence (H,M,L) _____
408	Water Infiltration	Flow (gpm) 100-2,000 _____, Depth to water table (ft in multiples of 5) 10-25 _____, Soil permeability (1-3): 1. high; 2. mid; 3. low _____, Level of protection (A,B,C,D,N) _____, Avg. temp. (F) _____, Level of confidence (H,M,L) _____
501	Transportation	Miles to offsite facility _____, Containerized wastes (drums) _____, Volume of bulk liquids (gal) _____, Volume of bulk solids (cy): Hazardous _____; Non-hazardous _____, Bulk sludges (cy) _____, Level of confidence (H,M,L) _____

Multilayered RCRA Cap Cost Module

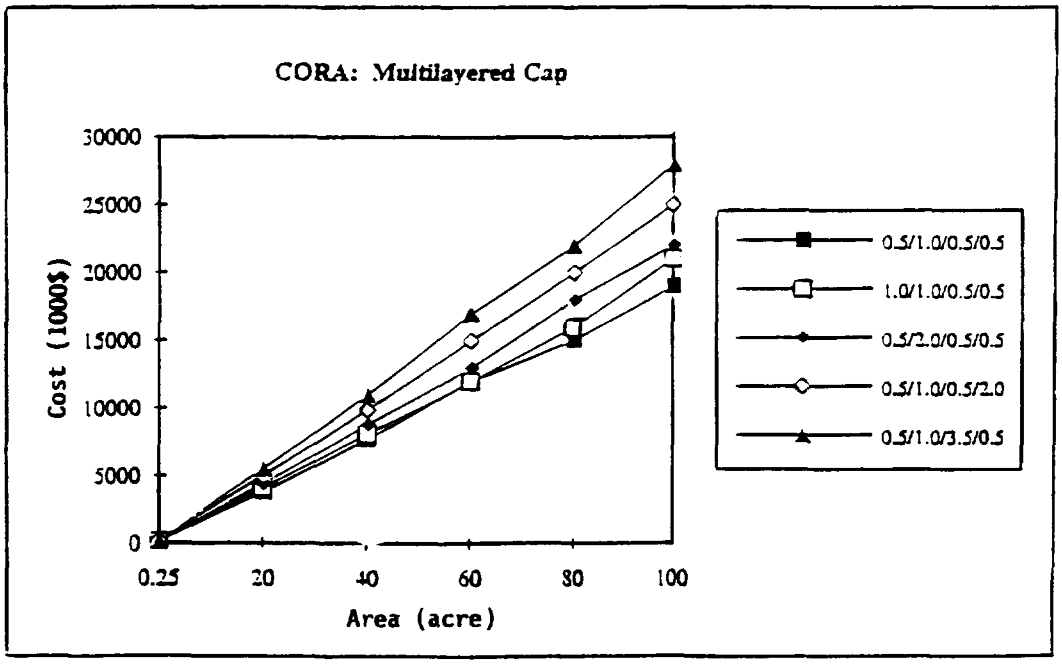
Input Parameters

Site area (acre):	0.25	20	40	Clay barrier thickness (ft):	2
	60	80	100	Filter fabric thickness (ft):	8
Soil leveling layer thickness (ft):		0.5	1.0	Above membrane protection:	none
Soil protective layer thickness (ft):		0.5	3.5	Below membrane protection:	none
Topsoil layer thickness (ft):		0.5	2.0	Average temperature:	70 F
Drainage layer thickness (ft):		1.0	2.0	Level of confidence:	high
Synthetic membrane thickness (mils):			60.0	Soil type:	topsoil

Output

	Capital Cost (1000$)					
Area (acre)	0.25	20	40	60	80	100
0.5/1.0/0.5/0.5	130	3800	7700	12000	15000	19000
1.0/1.0/0.5/0.5	140	4100	8100	12000	16000	21000
0.5/2.0/0.5/0.5	150	4400	8800	13000	18000	22000
0.5/1.0/0.5/2.0	170	5000	9900	15000	20000	25000
0.5/1.0/3.5/0.5	190	5500	11000	17000	22000	28000
1.0/2.0/0.5/0.5	150	4600	9300	14000	19000	24000
1.0/1.0/0.5/2.0	180	5200	10000	16000	21000	26000
0.5/2.0/0.5/2.0	190	5500	11000	17000	22000	28000
1.0/1.0/3.5/0.5	190	5800	11000	17000	23000	29000
0.5/2.0/3.5/0.5	200	6100	12000	18000	24000	31000
0.5/1.0/3.5/2.0	230	6700	13000	20000	27000	33000
1.0/2.0/0.5/2.0	190	5800	12000	17000	23000	29000
1.0/2.0/3.5/0.5	200	6300	13000	19000	25000	32000
1.0/1.0/3.5/2.0	230	6900	14000	21000	27000	34000
0.5/2.0/3.5/2.0	240	7200	14000	22000	29000	36000
1.0/2.0/3.5/2.0	240	7500	15000	22000	30000	37000
	O & M Cost (1000$)					
(all the same)	15	36	40	43	45	47

a/b/c/d a: soil leveling layer thickness (ft) c: soil protection layer thickness (ft)
b: drainage layer thickness (ft) d: topsoil layer thickness (ft)



Soil Flushing Cost Module

Input Parameters

Flush area (ft2):	100	200	300	400	500	600
	700	800	900	1000	1100	1200
	1300	1400	1600	1800	2000	
Availability of municipal water within 100 ft:			yes			
Level of protection:		none				
Average temperature:		70 F				
Level of confidence:		high				

Output

Length (ft)	Width (ft)	Area (*1000 ft2)	Capital Cost (1000$)	O & M Cost (1000$)
1000	100	100	470	58
1000	200	200	860	110
1000	300	300	1300	170
1000	400	400	1700	220
1000	500	500	2100	280
1000	600	600	2500	330
1000	700	700	2900	390
1000	800	800	3300	450
1000	900	900	3700	500
1000	1000	1000	4000	550
1000	1100	1100	4500	610
1000	1200	1200	4800	670
1000	1300	1300	5300	720
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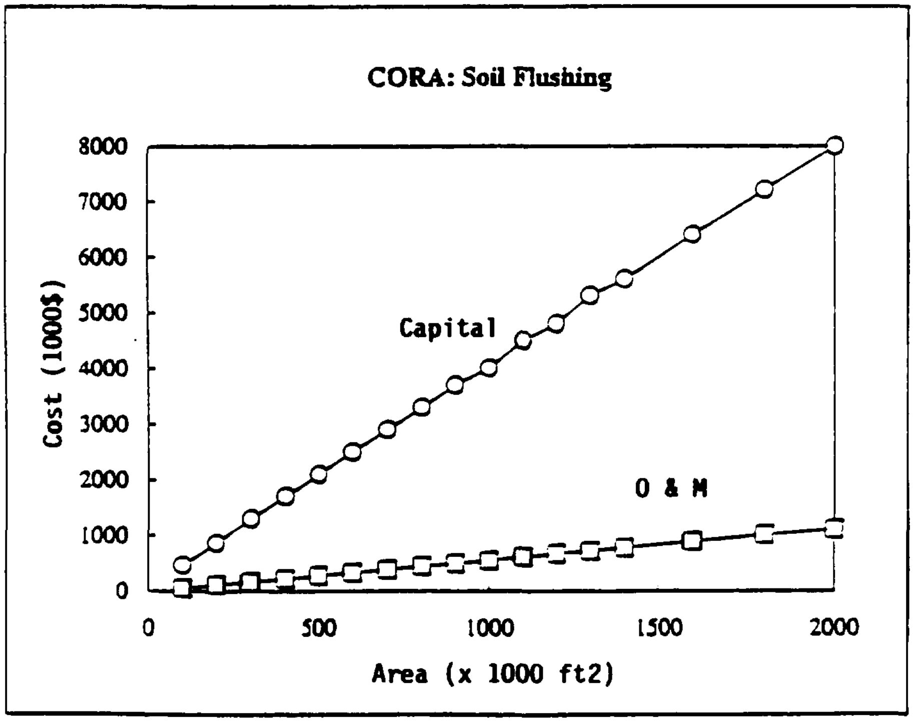
1000	1800	1800	7200	1000
1000	2000	2000	8000	1100



Solidification Cost Module

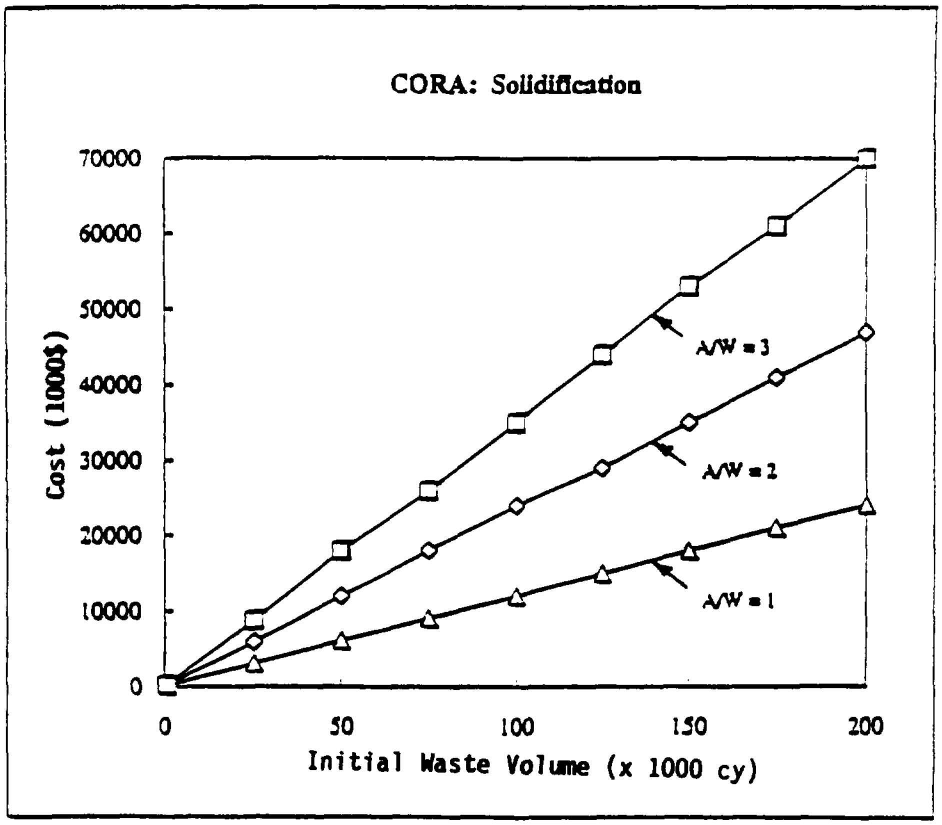
Input Parameters

Waste volume (cy):	500	25000	5000
	75000	100000	125000
	150000	175000	200000
Agent/waste proportion (w/w):[*]	1	2	3
% by weight of Portland cement:		100	
Unit weight of waste (pcf):	95		
Level of protection:	none		
Average temperature:	70 F		
Level of confidence:	high		

Output

Initial Waste Volume (x 1000 cy)	Capital Cost (1000$)			Stabilized Waste (cy)		
	A/W = 1	A/W = 2	A/W = 3	A/W = 1	A/W = 2	A/W = 3
0.5	120	180	240	1005	1511	2016
25	3100	5900	8800	50265	75531	100796
50	6100	12000	18000	100531	151061	201592
75	9100	18000	26000	150796	226592	302387
100	12000	24000	35000	201061	302122	403183
125	15000	29000	44000	251326	377653	503979
150	18000	35000	53000	301592	453183	604775
175	21000	41000	61000	351857	528714	705570
200	24000	47000	70000	402122	604294	806366

A/W: agent to waste weight ratio



[*] High binder to waste ratio required by model input

In Situ Stabilization Cost Module

Input Parameters

Volume to be solidified (cy):	500	1000	5000	Site conditions:	Easy (E)
	10000	50000	100000		Medium (M)
	150000	200000			Difficult (D)
Agent/waste proportion (w/w):*	1	2	3	Level of protection:	none
% by weight of Portland cement:	100			Average temperature:	70 F
Total unit weight of waste (pcf):	95			Level of confidence:	high

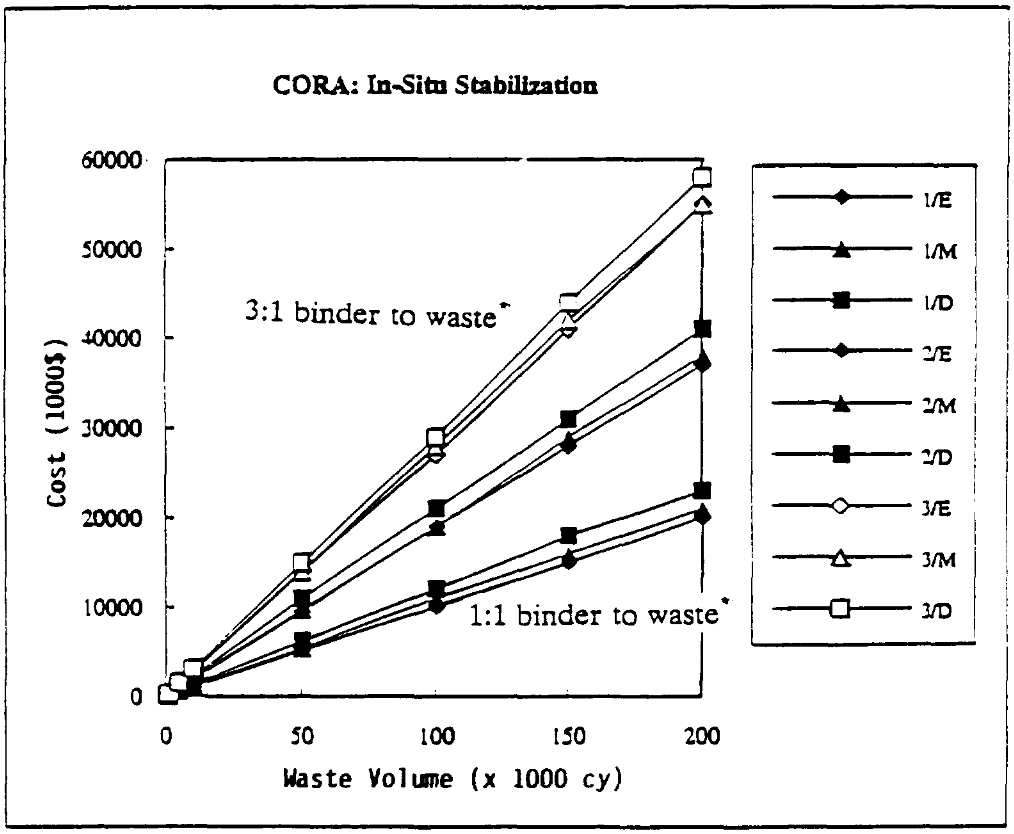
Output

Initial Waste Volume (x 1000 cy)	Capital Cost (x 1000$)								
	1/E	1/M	1/D	2/E	2/M	2/D	3/E	3/M	3/D
0.5	88	88	98	130	130	140	170	170	180
1	130	130	160	220	220	250	300	310	330
5	580	600	710	1000	1000	1100	1400	1500	1600
10	1100	1200	1400	2000	2000	2200	2800	2900	3100
50	5200	5400	6200	9500	9700	11000	14000	14000	15000
100	10000	11000	12000	19000	19000	21000	27000	28000	29000
150	15000	16000	18000	28000	29000	31000	41000	42000	44000
200	20000	21000	23000	37000	38000	41000	55000	55000	58000

1: agent/waste (w/w) = 1
E: site condition = easy

2: agent/waste (w/w) = 2
M: site condition = moderate

3: agent/waste (w/w) = 3
D: site condition = difficult



* High binder to waste ratio required by model input

APPENDIX J

SUMMARY OF MAJOR REGULATORY SOURCES OF CLEANUP GOALS

J.1 THE SAFE DRINKING WATER ACT (40 USC 300)

This act promulgated National Primary Drinking Water Regulations (40 CFR Part 141) and National Secondary Drinking Water Regulations (40 CFR Part 143). Primary maximum contaminant limits (MCLs) are enforceable standards for contaminants in public drinking water supply systems. They consider health factors, economic feasibility, and technical feasibility of removing a contaminant from a water supply system. Secondary MCLs are intended as guidelines to protect the public welfare. Contaminants covered are those that may adversely affect the aesthetic quality of drinking water, such as taste, odor, color, and appearance, and may deter public acceptance of drinking water provided by public water systems.

Maximum contaminant limit goals (MCLGs) exist for several organic and inorganic compounds found in drinking water. MCLGs are non-enforceable guidelines that consider only health factors.

During the Feasibility Study, MCLs or MCLGs may be used to determine remedial actions for groundwater and surface waters that are current or potential sources of drinking water. The NCP requires that MCLGs set at levels above zero (i.e., non-zero MCLGs) be attained during a CERCLA cleanup. In cases where the MCLG equals zero, the corresponding MCL is applicable (40 CFR 300.430 (e)(2)(i)(B) and (C)).

Underground injection control regulations (40 CFR Parts 144-147) provide for the protection of underground sources of drinking water. These may apply if remedial design includes reinjection of water.

J.2 CLEAN WATER ACT (33 USC 1251-1376)

This act sets standards and requirements for pollutant discharge. The National Pollutant Discharge Elimination System (NPDES) (40 CFR Parts 122 and 125) requires permits for the discharge of pollutants from any point source into the waters of the United States. General Pre-Treatment Regulations are enforceable standards promulgated under 40 CFR Part 403 for discharge to a publicly owned treatment works (POTW). They can be ARARs if groundwater remediation results in discharge to a POTW.

J.3 U.S. WATER QUALITY CRITERIA, 1986

The water quality criteria are standards for ambient surface water quality. The water quality criteria apply to specific bodies of water and typically are set by the states (40 CFR Part 131). They are not rules and they do not have regulatory impact. Rather, these criteria present guidance on the environmental effects of pollutants that can be a useful reference in environmental work. These water quality criteria may be included as "to be considered" conditions when setting cleanup goals.

J.4 RESOURCE CONSERVATION AND RECOVERY ACT

For RCRA requirements to be applicable or relevant and appropriate to CERCLA actions, a RCRA hazardous waste or a waste sufficiently similar to a RCRA hazardous waste must be present at the site. A review of site records and information may help determine if a RCRA hazardous waste is present.

There are several listed hazardous wastes from nonspecific sources (40 CFR 261.31), specific sources (40 CFR 261.32), and discarded commercial chemical products, off-specification species, container residues, and spill residues thereof (40 CFR 261.33) that are regulated under RCRA. RCRA waste types and Land Disposal Restrictions (LDRs) required treatment standards are summarized in Appendix E.

Wastes contaminated with metals may be determined to be characteristic RCRA wastes as defined in 40 CFR Part 261, Subpart C, if the waste exhibits one of the following characteristics: ignitability, corrosivity, reactivity, or toxicity.

J.4.1 Land Disposal Restrictions

RCRA prohibits land disposal of untreated hazardous wastes. For treated hazardous waste to be disposed on land (e.g., in a landfill or by deep-well injection), Hazardous and Solid Waste Amendments (HSWA) required EPA to develop, on a phased schedule, contaminant concentration levels or waste treatment methods that would reduce substantially the toxicity or mobility of hazardous constituents. Alternatively, untreated hazardous waste could be disposed in a unit from which there would be "no migration." By May 1990, EPA had developed restrictions and waste treatment standards for all wastes listed or identified as hazardous at the time that HSWA became law in 1984. Requirements to comply with these restrictions and standards were phased in over a period of several years; the last became effective in May 1993. In addition, on August 8, 1992, EPA published a final rule establishing treatment and recycling standards for 20 "newly listed" wastes that were identified or listed after HSWA was signed into law.

In addition to normal wastes or contaminated soils and water, debris such as wood, rocks, or manmade materials that has been contaminated may be present at CERCLA sites and pose difficulties for cleanup. Under RCRA, debris contaminated with hazardous wastes is treated as hazardous waste and is regulated under the land disposal regulations. EPA finalized the treatment standards for debris in 57 FR 37194 (August 18, 1992).

Hazardous debris is prohibited from land disposal (40 CFR 268.35) unless it has been treated to the standards specified in 40 CFR 268.45. Under 40 CFR 268.45, hazardous debris must be treated for each "contaminant subject to treatment" as defined in the regulation using the technology or technologies specified in the regulations (see Table 1 in 40 CFR 268.45). "Contaminants subject to treatment" include toxicity characteristic debris, debris contaminated with listed waste, and cyanide-reactive debris. Hazardous debris that has been treated using one of the specified extraction or destruction technologies and that does not exhibit a characteristic of hazardous waste after treatment is not a hazardous waste and does not need to be managed in a Subtitle C hazardous waste facility. However, hazardous debris that is treated with an immobilization technology specified in the regulations is considered hazardous waste and must be handled in a permitted facility. Residue from treatment of hazardous debris must be separated from the treated debris using simple physical or mechanical means and generally is subject to the waste-specific treatment standards for the waste contaminating the debris, with a few minor exceptions.

The EPA renewed the exemptions of debris contaminated with hazardous wastes from LDRs beyond the May 8, 1993 expiration. The extension was granted due to limited capacity availability. To use the exemption, the generator must show that a genuine effort was made to locate treatment capacity. The estimated volume of hazardous debris generation in 1994 was 1.2 to 1.8 million tons. About 30% of this amount would come from Superfund sites (Superfund Week, 1993).

The EPA has proposed alternative treatment standards for soil contaminated with LDR-prohibited hazardous wastes. The proposed standards are intended to encourage consideration of the full range of innovative technologies available to treat contaminated soil. Several approaches are proposed as a basis for review and comment (58 FR 48092, September 14, 1993).

APPENDIX K

GLOSSARY

Abrasives – powdered, granular, or solid materials used to grind, smooth, cut, or polish other substances.

Absorption – assimilation of fluids into interstices.

Acidity – the quantitative capacity of materials to react with hydroxyl ions.

Active Biomass – living plants, animals, or microorganisms.

Additives – materials included in the binder to improve the S/S process. Examples of some types of additives are (1) silicates or other materials that alter the rate of hardening, (2) clays or other sorbents to improve retention of water or contaminants, or (3) emulsifiers and surfactants that improve the incorporation of organic compounds.

Administrative Record – material documenting EPA's selection of cleanup remedies at Superfund sites, usually placed in the information repository near the site.

Adsorption – attraction of solid, liquid, or gas molecules, ions, or atoms to particle surfaces by physicochemical forces. The adsorbed material may have different properties from those of the material in the pore space at the same temperature and pressure due to altered molecular arrangements.

Advection – unidirectional, progressive bulk movement, such as water under the influence of a hydraulic gradient.

Alkalinity – the quantitative capacity of aqueous media to react with hydrogen ions.

Amalgamation – in general, the formation of a solid solution of two dissimilar metals. As used in mineral processing, a method for recovering metals from solids or sludges by treatment with mercury to form a metal/mercury alloy.

Anion – an ion that is negatively charged.

Applicable or Relevant and Appropriate Requirements (ARARs) – Cleanup standards, standards of control, and other substantive requirements, criteria, or limitations promulgated under Federal, State, or local environmental laws or facility siting laws that are *applicable*, that specifically address a hazardous substance, pollutant, contaminant, remedial action, location, or other circumstance found at CERCLA sites, or are *relevant and appropriate*, that address problems or situations similar to those encountered at CERCLA sites (40 CFR 300.5, pp. 7 and 12).

Aquifer – underground formation of sand, soil, rock, or gravel that can store and supply groundwater to wells or springs.

Asphalt – a brown, black, hard, brittle, or plastic bituminous material composed principally of hydrocarbons. It is found in nature or can be prepared by pyrolysis of coal tar, certain petroleums, and lignite tar. It melts on heating and is insoluble in water but soluble in gasoline.

Bartles-Mozley Table – a multideck gravity concentration shaker table using an orbital motion rather than pure horizontal motion to develop shear in the layer of particles on the table.

Bentonite – a clay formed from volcanic ash decomposition and largely composed of montmorillonite and beidellite. Usually characterized by high swelling on wetting.

Best Demonstrated Available Technology (BDAT) – a concentration or technology-based treatment standard applied to RCRA waste under the Land Disposal Restrictions.

Binder – a cement, cement-like material, or resin (possibly in conjunction with water, extender, or other additives) used to hold particles together.

Bioaccumulation – the transfer of metal from a contaminated matrix to biomass.

Biobeneficiation – chemical action or particle surface modification by microorganisms to improve physical separation of a contaminated solid matrix into contaminant-rich and contaminant-poor streams.

Bioconcentration – increase of metal contaminant concentration by the metabolic activity of a suitable animal, plant, or microorganism.

Bioleaching – a process developed in the mining industry as an inexpensive method to recover metals. The technology involves microbial solubilization of metals from a solid or semisolid matrix.

Biomagnification - a process whereby certain substances such as pesticides or heavy metals move up the food chain, work their way into a river or lake and are eaten by aquatic organisms such as fish which in turn are eaten by birds, other animals, or humans. The substances become concentrated in tissues or internal organs as they move up the chain.

Biological Treatment Options – the application of biological metabolism or materials to the treatment of metals.

Bitumen – naturally occurring or pyrolytically-obtained dark or black colored, tarry hydrocarbons consisting almost entirely of carbon and hydrogen, with very little oxygen, nitrogen, or sulfur.

BNA – base, neutral, and acid (organic) compounds, a chemical analysis identification for organic compounds based on extraction properties.

Buffer – a solution selected or prepared to minimize changes in pH (hydrogen ion concentration). Also known as buffer solution.

Calcination – in general, heating a material to a temperature below its melting point to cause chemical decomposition or phase transition other than melting. Used in this document to designate a process for further refining the mixed cadmium, lead, and zinc oxide product from a Waelz kiln. By controlling the temperature profile in the kiln and using oxidizing conditions, the cadmium and lead are volatilized and oxidized while zinc oxide remains as a solid. The cadmium and lead fumes are collected for further refining to separate cadmium and lead for reuse.

Capping Systems – capping systems are designed to reduce surface water infiltration, control gas and odor emissions, improve aesthetics, and provide a stable surface over the waste.

Cation – a positively-charged atom or group of atoms.

Cation Exchange Capacity – quantity of available hydrated cation exchange sites, usually expressed as milliequivalents per unit mass of volume.

Cement – a mixture of calcium aluminates and silicates made by combining lime and clay under heating.

J.4.2 Corrective Action Management Units

EPA recently amended the regulations for RCRA facilities to allow more flexibility in treatment of waste generated during corrective actions (58 FR 8658, February 16, 1993). These regulations allow the EPA Regional Administrator to designate Corrective Action Management Units (CAMUs) at a RCRA facility for treatment of remediation wastes; however, the regulations specifically exclude using CAMUs to treat normal "as-generated" wastes. Although these regulations were developed specifically for corrective actions at RCRA hazardous waste facilities, the regulations also may be applied as ARARs to CERCLA sites, particularly where CERCLA remediation involves management of RCRA hazardous wastes. In the past, wastes that were removed from the ground (e.g., excavation of contaminated soils) were required to comply with the treatment standards established under the LDR. An important provision of the new regulations is the specification in 40 CFR 264.552(a)(1) and (2) that:

1. Placement of remediation wastes into or within a CAMU does not constitute land disposal of hazardous wastes

2. Consolidation or placement of remediation wastes into or within a CAMU does not constitute creation of a unit subject to MTRs (minimum technology requirements)

As a result, an area or several areas at a RCRA facility (or CERCLA site) can be designated as a CAMU and the wastes can be removed from the ground, treated, and replaced within the boundaries of that CAMU without being required to comply with the LDR treatment standards. EPA's goal in issuing these regulations is to encourage the use of more effective treatment technologies at a specific site. The regulatory impact analysis of the CAMU regulation indicated that the regulation will result in more onsite waste management, less reliance on incineration, greater reliance on innovative technologies, and a lower incidence of capping waste in place without treatment.

J.5 THE CLEAN AIR ACT (CAA) OF 1990 (42 USC 7401-7642)

The CAA promulgated the following standards that may or may not be ARAR at the site due to the following reasons:

- *National Ambient Air Quality Standards (NAAQS)*. NAAQS apply to total suspended particulate, sulfur dioxide, nitrogen dioxide, carbon monoxide, ozone, and lead concentrations in ambient air, and are not applicable to individual emission sources. "Prevention of significant deterioration" (PSD) regulations may apply preconstruction guidelines and monitoring to statutory sources.

- *New Source Performance Standards (NSPS)* were developed for specific industrial categories to provide a ceiling for emissions from new sources.

- *National Emission Standards for Hazardous Air Pollutants (NESHAPS)* regulate asbestos, beryllium, mercury, vinyl chloride, coke oven emissions, benzene, radionuclides, and inorganic arsenic.

J.6 OCCUPATIONAL SAFETY AND HEALTH ACT (OSHA) (29 USC 651-678 AND 29 CFR PARTS 1904, 1910, AND 1926)

This act provides occupational safety and health requirements applicable to workers engaged in onsite field activities. The regulations are applicable to onsite work performed during implementation of a remedial action. They are applicable to nearly all remedial action options.

J.7 DOT RULES FOR HAZARDOUS MATERIALS TRANSPORT (49 USC 1801-1813) (49 CFR PARTS 107 AND 171-177)

These rules regulate the transport of hazardous materials including packaging, shipping equipment, and placarding. These rules are considered applicable to hazardous and nonhazardous wastes shipped offsite for laboratory analysis, treatment, or disposal.

Centrifugation – uses centrifugal force created by a rotating bowl instead of gravity to bring about separation.

CERCLA Hazardous Substance – any substance, pollutant, or contaminant as defined in CERCLA sections 101(14) and 101(33), except where otherwise noted in the Hazard Ranking System (see 40 CFR 302.4).

CERCLA Hazardous Wastestream – any material containing CERCLA hazardous substances that was deposited, stored, disposed, or placed in or migrated to a site being evaluated by the HRS; any material listed in the NPL.

CERCLA Waste – a term with no regulatory meaning that is often used as a shortened form of *CERCLA hazardous wastestream.*

Characteristic Waste – see *RCRA characteristic waste*

Chemical Leaching – an option for metal contaminants bound so tightly to the solid matrix that soil washing is not effective. The methods and equipment used in chemical leaching are similar to those used for soil washing. The major requirement is to obtain good contact between the contaminated matrix and the extraction solution.

Chemical Reduction – a process in which the oxidation state of an atom is decreased.

Chemical Oxidation – alters the oxidation state of an atom through loss of electrons.

Chemical Neutralization – involves equalizing the concentrations of hydrogen and hydroxide ions in a solution.

Chemical Treatment Options – various treatment agents that may be added to the contaminated matrix to adjust conditions to favor less toxic or less mobile forms of metal contaminants.

Classification – a technique of separating particles into two or more fractions based on the velocity with which the particles fall through air (*air classification*) or a water medium (*hydroclassification*).

Clay – fine-grained soil or the fine-grained portion of soil that can be made to exhibit plasticity (putty-like properties) within a range of water contents and that exhibits considerable strength when air-dried.

Colloid – the phase of a colloidal system made up of particles having dimensions of 1 to 1000 nanometers and which is dispersed in a different phase.

Colloidal System – an intimate mixture of two substances, one of which, the *dispersed phase* (or *colloid*), is uniformly distributed in a finely divided state through the second substance, the *dispersion medium.*

Combustion – rapid reaction of a gas, liquid, or solid fuel with an oxidizer, which releases heat and usually light.

Compressive Strength (unconfined or uniaxial compressive strength) – the load per unit area at which an unconfined cylindrical specimen of soil or rock will fail in a simple compression test. Commonly the failure load is the maximum that the specimen can withstand in the test.

Containment Technologies – reduce the mobility of metal contamination through construction of physical barriers (containment) to reduce the flow of water through contaminated media or the flow of contaminated groundwater.

Contaminant – typically undesirable minor constituent that renders another substance impure.

Corrosiveness Characteristic – exhibiting the hazardous characteristic of corrosivity due to extreme pH or failing under the test conditions defined in 40 CFR 261.22.

Cost – refers to the initial capital cost to design, purchase, and install the remediation option as well as the cost of operating and maintaining the option.

Data Quality Objective (DQO) – a planned quantitative measure of precision, accuracy, and completeness of data.

Density, Apparent (of solids and liquids) – the mass of a unit volume of a material at a specified temperature. Only the volume that is impermeable is considered.

Density, Bulk (of solids) – the mass of a unit volume of the material at a specified temperature.

Destruction-removal Efficiency (DRE) – The combined efficiencies of one or more processes intended to reduce the target contaminant(s). The DRE may be expressed as a ratio or percentage.

Dewatering – reducing the water content of a slurry.

Diffusion – movement of molecules towards an equilibrium driven by heat or concentration gradients (mass transfer without bulk fluid flow).

Diffusivity – diffusion coefficient, the weight of material, in grams, diffusing across an area of 1 square centimeter in 1 second due to a unit concentration gradient.

Dimensional Stability – the ability of the S/S waste to retain its shape.

Direct Capital Costs – include costs for remedial action construction, component equipment, land and site development, buildings and services, relocation of affected populations, and disposal of waste materials.

Disposal Facility – a facility or part of a facility at which waste is intentionally placed into or on any land or water, and at which waste will remain after closure.

Durability – the ability of S/S wastes to resist physical wear and chemical attack over time.

Dynamic Leach Test (DLT) – a leaching test where the specimen is exposed to an actual or simulated flow of the leachant.

Economic Evaluation/Cost Analysis (EE/CA) – CERCLA technology screening process for a removal action per 40 CFR 300.415.

Electrokinetics – removes metals and other contaminants from soil and groundwater by applying an electric field in the subsurface.

Electrowinning – recovery of elemental metal from water solution by application of electrical potential.

Embedment – the incorporation of waste masses into a solid matrix before disposal.

Emerging Technologies – technologies that are still being designed, modified, and tested in the laboratory and are not available for full-scale implementation (e.g., plasma-arc ultrahigh-temperature process, or hydrodehalogenation with atomic or molecular hydrogen under the presence of heat, pressure, and catalyst).

Emulsifier – a substance used to produce an emulsion of two liquids which do not naturally mix.

Emulsion – a colloidal mixture of two immiscible fluids, one being dispersed in the other in the form of fine droplets.

Equilibrium Leach Test (ELT) – a leaching test in which, under the conditions of the test, an equilibrium between the specimen and the leachant is attained.

Ettringite – a mineral composed of hydrous basic calcium and aluminum sulfate. The formula for ettringite is $Ca_6Al_2(SO_4)_3(OH)_{12} \cdot 26\ H_2O$.

Expression – physical removal of liquid from a solid/liquid mixture by application of pressure.

Extender – an additive the primary function of which is to increase the total bulk of the S/S-treated waste.

Extraction Procedure Toxicity Test (EP Tox) – a regulatory leaching test used since 1980 to determine if a waste is toxic (40 CFR Part 261, Appendix II).

Fate and Transport – analysis of movements and transformations of contaminants through the environment from a source to a receptor.

Feasibility Study (FS) – a study undertaken to develop and evaluate options for a treatment process.

Filtration – a process that involves passing a slurry through a porous medium in which the solids are trapped and the liquid passes through.

Flame Reactor – a treatment method developed by the Horsehead Resource Development Company (HRD) to recover cadmium, lead, and zinc from complex solid materials. The HRD Flame Reactor technology is a two-stage treatment method. In the first stage, carbonaceous fuel is combusted with oxygen-enriched air under fuel-rich conditions (burner section). The combusted waste is pneumatically injected into the hot (2,200 to 2,500°C) reducing flame in the second stage (reactor section). The intensive process conditions allow reaction times to be short (less than one-half second) and permit a high waste throughput. Close control of the operating parameters enables extraction of valuable metals and destruction of hazardous organic constituents.

Flue Gas Desulfurization (FGD) – a pollution abatement process.

Fly Ash – the finely divided residue from the combustion of ground or powdered coal which is transported from the firebox through the boiler by flue gas.

Fourier Transform Infrared Spectroscopy (FTIR) – a microcharacterization method.

Free Water – water that is free to move through a soil or rock mass under the influence of gravity.

Freeze/Thaw Cycle – alternation of a sample temperature to allow determination of weight loss and visual observation of sample disintegration resulting from phase change from water to ice.

Froth Flotation – involves more chemistry than the other physical separation techniques and is based on the fact that different minerals have different surface properties. These differences in surface properties can be accentuated by adding suitable chemicals to a slurry containing the minerals. Air is sparged from the bottom of a tank or column containing the slurry. The desired metal selectively attaches to the air bubbles and rises to the top, and the froth that forms at the top is collected to recover the metal.

Fumes – fine particulates that evaporate and recondense to form the fume.

Geomembrane Curtains – vertical barriers used in applications where chemical degradation of conventional grouts is anticipated. Geomembranes can be useful as liners in lagoons and landfills where contaminant levels in the leachate may be high.

Gravity Concentration – a physical separation technique based on particle density.

Groundwater – water found beneath the earth's surface that fills the pores between materials such as sand, soil, or gravel.

Grout – as used in soil and rock grouting, a material injected into a soil or rock formation to change the physical characteristics of the formation. The term "grout" is not used in this document but is frequently encountered in the S/S industry as a synonym for the term "binder."

Grout Curtains – containment barriers formed by grout injection.

Hazardous Characteristics – ignitable, corrosive, reactive, and toxic as defined in 40 CFR Part 261.10.

Hazard Ranking System (HRS) – the primary mechanism for considering sites for inclusion on the NPL.

Hazardous Substance List (HSL) – a list of designated CERCLA hazardous substances as presented in 40 CFR 302.4.

Hazardous Waste – see *RCRA hazardous waste*, *CERCLA hazardous substance*, and *CERCLA hazardous wastestream*.

Heat of Hydration (in S/S reactions) – the heat generated due to the reaction of cementitious or pozzolanic materials with water.

Heavy Medium Separation – heavy medium separation is based on a density separation of particles as they settle in a liquid (heavier than water) the density of which is between that of the two minerals to be separated.

Horizontal Barriers – low-permeability structures placed horizontally, typically under the contaminated volume, to contain the contaminants.

Hydrate – a compound containing structural water.

Hydrocyclone – the hydrocyclone consists of a vertical cone into which the feed (in the form of a slurry) is introduced tangentially at the top. A vortex is created with a low-pressure zone along the vertical axis of the cone. Faster settling particles (those having larger size or higher density) are accelerated to the wall of the cyclone by centrifugal force, and move in spiral form along the wall down to the bottom opening.

Hydrometallurgical Separation – a process in which aqueous or organic solutions are used to chemically extract metals from a solid matrix.

Hydrotreating – a catalytic process used in oil refining to remove impurities such as oxygen, sulfur, nitrogen, or unsaturated hydrocarbons.

Ignitability Characteristic – exhibiting the hazardous characteristic of ignitability as defined in 40 CFR 261.21.

Immobilization – the reduction in the ability of contaminants to move through or escape from S/S-treated waste.

Immobilization Treatment Options – immobilization treatment options reduce contaminant mobility by containment or by S/S.

Implementability – The feasibility of implementing a technology from a technical and administrative standpoint must be determined, and the availability of various goods and services as well as monitoring requirements should be considered.

Inactive Biomass – non-living plants, animals, or microorganisms.

Incineration – a treatment technology involving destruction of waste by controlled burning at high temperatures.

Indirect Capital Costs – include costs for engineering expenses, contingencies, and project management.

Information Repository – file of data and documents located near a Superfund site.

Inhibitor – a material that stops or slows a chemical reaction from occurring. Used in this document to apply to stopping or slowing the setting of S/S-treated material.

Innovative Treatment Technologies – alternative treatment technologies (i.e., those "alternative" to land disposal) for which use at Superfund-type sites is inhibited by lack of data on cost and performance.

Interference (S/S) – an undesirable change in the setting of the S/S material resulting in lower strength, poorer leach resistance, or evolution of noxious or hazardous gases, or other degradation of the S/S-treated material.

Interstitial – see *pore water*.

Ion – an atom or molecule which by loss or gain of one or more electrons has acquired a net electric charge.

Ion Exchange – a chemical reaction in which ions associated with charged sites in a solid matrix are exchanged, mole for mole, with ions of like charge in solution.

Ion Partitioning – ions partition from the water phase to a solid mineral surface by physical adsorption, chemical adsorption, and incorporation into a mineral phase.

Jig – one of the oldest gravity separation devices, this device achieves particle stratification by introducing the feed particles into a pulsating water column.

Kaolin – a variety of clay containing a high percentage of kaolinite.

Kaolinite – a common clay mineral having the general formula $Al_2(Si_2O_5)(OH_4)$.

Kiln – a heated and usually rotating enclosure used for drying, burning, or firing materials such as ore or ceramics. In this document *kiln* typically refers to a kiln used for production of lime or cement.

Kiln Dust – fine particulate by-product of cement production or lime calcination.

Landfill – a subgrade waste-holding or disposal facility.

Leachability – a measure of release of constituents from a waste or S/S waste. Leachability is one measure of the mobility of a constituent. High leachability means high constituent mobility.

Leachant – liquid that comes in contact with a material either from natural exposure (e.g., water in a disposal site) or in a planned test of leachability. The typically used leachants are pure distilled water or water containing salts, acids, or both.

Leachate – any liquid, including any suspended components in the liquid, that has soaked, percolated through, or drained from material during leaching.

Leaching – the release of constituents from a solid through contact with the leachant. The leaching may occur by either natural mechanisms at waste sites or as part of a laboratory leaching test.

Leaching Agent – leachant.

Leaching Rate – the amount of a constituent of a specimen or solid waste form which is leached during a unit of time (usually normalized by sample volume, area, or weight).

Leaching Resistance – the inverse of leachability. High leach resistance means low contaminant mobility.

Leaching Test – exposure of a representative sample of contaminated waste, S/S-treated waste, or other material to a leachant under controlled conditions to measure the release of constituents.

Lime – specifically, calcium oxide (CaO); also, loosely, a general term for the various chemical and physical forms of quicklime, hydrated lime, and hydraulic hydrated lime.

Listed Waste – see *RCRA listed waste*.

Long-Residence-Time Melters – these waste vitrification melters use a molten reservoir that allows a relatively long residence time for the waste to mix and blend with previously fed material and allow greater time average variability in the feed stream for longer times without adversely influencing the uniformity of the discharged material.

Long-Term Effectiveness – refers to the ability of an alternative to maintain reliable protection of human health and the environment over time once the cleanup levels have been met.

Long-Term Stability – the ability of S/S wastes to maintain their properties over time while exposed to the environment.

Macroencapsulation – a process of encasing a mass of solid or S/S-treated waste in a protective layer, such as bitumen (thermoplastic).

Magnetic Separation – magnetic separation is based on the differences in magnetic properties of the various minerals, especially for separating ferrous from nonferrous materials.

Matte – a mixture of metal sulfides produced by pyrometallurgical processing of sulfide ores.

Mercury Cell Chloralkali Process Sludge (K106) – a mercury-bearing sludge resulting from treatment of effluents from electrolytic processing to generate chlorine gas and sodium hydroxide.

Metals in Polymer Matrices – metals incorporated in polymer matrices to act as fillers, improve mechanical properties, or provide colors.

Microencapsulation – containment of the contaminants on a microscopic or molecular scale.

Microstructure – the structure of an object or material as revealed by a microscope at a magnification greater than 10 times.

Mixer – machine employed for blending the constituents of grout, mortar, or other mixtures.

Modified Clays – clays (such as bentonite) that have been modified by ion exchange with selected organic compounds that have a positive charged site (often a quaternary amine), hence rendering the clay/organo complex hydrophobic.

Monitoring – collection of data on contaminants in different environmental media (air, surface or groundwater, sediments, soils) to determine extent and impact or effectiveness of a cleanup action.

Monofilled Waste Extraction Procedure (MWEP) – a leaching test.

Monolith – a free standing solid consisting of one piece.

Monomer – a simple molecule which is capable of combining with a number of like or unlike molecules to form a polymer.

Montmorillonite – a group of clay minerals characterized by a weakly bonded sheet-like internal molecular structure; consisting of extremely finely divided hydrous aluminum or magnesium silicates that swell on wetting, shrink on drying, and have ion exchange capacity.

Multimedia – air, land, and water.

Multiple Extraction Procedure (FMEP) – a leaching test in which the sample is repeatedly leached with fresh batches of leachant.

National Oil and Hazardous Substances Contingency Plan (NCP) – provides the organizational structure and procedures for preparing and responding to discharges of oil and releases of hazardous substances, pollutants, and contaminants (40 CFR 300.1).

National Priorities List (NPL) – list of CERCLA sites (40 CFR Part 300, Appendix B).

Nonaqueous-phase Liquids (NAPLs) – organic fluids that will partition to a separate organic phase or to the vapor, water, or sorbed phases depending on the volume of organic present and the site and contaminant properties.

Nuclear Magnetic Resonance Spectroscopy (NMR) – a microcharacterization method.

Operation and Maintenance (O&M) – O&M costs are those that must be incurred after construction, but during the remediation phase, to ensure continued efficiency of the treatment process. The major components of O&M costs include: operating labor; maintenance materials and labor; auxiliary materials and energy; purchased services; administrative costs; insurance, taxes, and licenses; and maintenance reserve and contingency costs.

Oxidation/Reduction (Biological) – the oxidation or reduction of a metal as a result of a reducing agent produced by the organism.

Oxidation/Reduction (Chemical) – the oxidation (or reduction) of a metal due to chemical action.

Paint Filter Test (PFT) – a physical characterization test.

Partitioning – equilibrium distribution of a solute between two material phases.

parts per billion (ppb) – units commonly used to express concentrations of chemicals in environmental media. For example, 1 ounce of a chemical or substance in 1 billion ounces of soil or water is 1 ppb.

parts per million (ppm) – units commonly used to express concentrations of chemicals in environmental media. For example, 1 ounce of a chemical or substance in 1 million ounces of soil or water is 1 ppm.

Percolation – movement of water under hydrostatic pressure or gravity through the smaller interstices of rock, soil, wastes, or S/S-treated wastes.

Performance Criterion – a measurable performance standard set for an individual property or parameter.

Performance Indicator – an easy-to-measure property or parameter selected to characterize the S/S process or S/S-treated waste.

Permeability – a measure of flow of a fluid through the tortuous pore structure of the waste or S/S-treated waste. It is expressed as the proportionality constant between flow velocity and the hydraulic gradient. It is a function of both the fluid and solid media. If the permeating fluid is water, the permeability is termed as hydraulic conductivity.

Phase (of a material) – a region of a material that is physically distinct and is homogeneous in composition and morphology.

Physical Separation/Beneficiation – these techniques involve the physical separation of particles from each other based on size, weight, density, surface condition, or other physical characteristics.

Plume – area of or extent of contamination in groundwater.

Polymer – a chemical with repetitive structure formed by the chemical linking of single molecules (monomers).

Pore – a small cavity or void in a solid.

Pore Size Distribution – variations in pore sizes in solids; each material has its own typical pore size distribution and related permeability.

Pore Water – water contained in voids in the solid material.

Porosity – the ratio of the aggregate volume of voids or interstices to the total volume of the medium.

Portland Cement – a hydraulic cement produced by pulverizing clinker consisting essentially of hydraulic calcium silicates, usually containing one or more of the forms of calcium sulfate.

Potentially Responsible Party (PRP) – potentially liable for the contamination and cleanup of CERCLA sites.

Pozzolan – a siliceous or siliceous and aluminous material, which in itself possesses little or no cementitious value but will, in finely divided form and in the presence of moisture, chemically react with calcium hydroxide at ordinary temperatures to form compounds with cementitious properties. The term is derived from an early source of natural pozzolanic material, Pozzuoli, Italy.

Proposed Plan – Superfund public participation fact sheet that summarizes the preferred cleanup strategy, the rationale, and the RI/FS.

Proven (or Established) Technologies – technologies that have been used on a commercial scale and established for use in full-scale remediations (e.g., on-site or off-site incineration, capping, S/S.

Pyrometallurgical Separation – methods using high-temperature processes to treat a metal-contaminated solid for recovery of metals as metal, metal oxide, ceramic product, or other useful form.

RCRA Characteristic Waste – any solid waste exhibiting a characteristic of ignitability, corrosivity, reactivity or toxicity, as defined in 40 CFR 261, Subpart C.

RCRA Hazardous Waste – any RCRA solid waste, as defined by 40 CFR 261.3, that is not excluded from regulation under 40 CFR 261.4 and that meets any one of the characteristic or listing criteria (including mixtures) described in 40 CFR 261.3(a)(2).

RCRA-Listed Waste – any solid waste listed in 40 CFR 261, Subpart D; or a mixture that contains a solid waste listed in 40 CFR 261, Subpart D that has not been excluded under the provisions of 40 CFR 261.3 in accordance with 40 CFR 260.20 or 40 CFR 260.22.

RCRA Solid Waste – any garbage, refuse, or sludge; or any solid, liquid, semi-solid or contained gaseous material that is: (1) discarded, (2) no longer to be used for its original purpose, or (3) a manufacturing or mining by-product and is not excluded by the provisions of 40 CFR 261.4(a). For more detail, see 40 CFR 260, Appendix I. Also note that the definition of solid waste includes materials that are not "solids" in the normal sense of the word.

Reactivity Characteristic – exhibiting the hazardous characteristic of reactivity as defined in 40 CFR 261.23.

Record of Decision (ROD) – a document prepared to explain and define the final remedy selected for a CERCLA site (40 CFR 300.430 (f)(4)(i)).

Redox – abbreviation for oxidation-reduction, now accepted as a word.

Reduction of Toxicity, Mobility, and Volume – the three principal measures of the overall performance of a remediation option. The 1986 amendments to the Superfund statute emphasize that, whenever possible, the EPA should select a remedy that uses a treatment process to permanently reduce the level of toxicity of contaminants at the site, the spread of contaminants away from the source, and the volume or amount of contaminants at the site. The primary goal of any treatment technology should be to adequately safeguard human health and the environment.

Refractory Bricks – high-performance ceramic materials used to line high-temperature processing equipment.

Remedial Investigation/Feasibility Study (RI/FS) – see *Remedial Investigation (RI)* or *Feasibility Study (FS)*.

Remedial Investigation (RI) – a process undertaken by the lead agency to determine the nature and extent of the problem presented by a CERCLA site (40 CFR 300.430(d)).

Remediation Manager (RM) – the official designated by the lead agency to coordinate, monitor, or direct remedial or other response actions under subpart E of the NCP (40 CFR 300.5).

Residual Liquid – free liquid remaining in the S/S-treated waste after treatment.

Responsible Party (RP) – persons or corporate entities found to be responsible for contamination and cleanup at a CERCLA site.

Retorting – thermal treatment to extract a metal from a solid matrix by vaporization.

Roasting – thermal treatment to effect a chemical change prior to smelting. For example, heating mercury compounds to form mercury metal or heating metal sulfides in air to form metal oxides.

ROD – see *Record of Decision*.

Rotary Kiln – a cylindrical kiln with the axis inclined at a slight angle. The kiln rotates around the axis.

Scanning Electron Microscopy (SEM) – a microcharacterization method.

Screening – the process of segregating solids according to particle size by passing the solids through a sieve with specifically sized openings.

Sedimentation – the settling of solid particles in water.

Separation/Concentration Treatment Options – separation/concentration technologies employ physical, chemical, or thermal processes to separate contaminants from the associated medium. These technologies do not alter the fundamental nature of the contaminant toxicity or mobility, but rather function to collect contaminants into a concentrated form and smaller volume or to transform them into a different medium (such as by soil washing) that is easier to handle for further treatment and disposal.

Sequential Chemical Extraction (SCE) – a leaching test with a variety of aqueous chemicals used sequentially to characterize the contaminant bonding.

Sequential Extraction Test (SET) – a leaching test with a series of sequential acid extractions used to determine the sample buffering capacity.

Shaking Table – the shaking table operates according to a principle similar to that of the spiral concentrator. This device consists of a slightly inclined deck to which a 25% solids slurry is introduced at the higher corner. The flowing film separates the small dense particles (which move quickly to the lower, slower-moving layer of the film) from the coarse, light particles as shown in Figure 4-14. The effect is enhanced by vibrating the table at right angles to the water flow in a slow forward stroke and a fast return stroke. The net effect is that the particles move diagonally across the table. Stratification is enhanced by riffles that run along the long axis of the table parallel to the vibrations. The small, dense particles settle down quickly into the riffles near the feed end. These particles travel along the riffles to the side of the table. The coarser, lighter particles go over the riffles to the front of the table. Concentrate, middlings, and tailings can be isolated as required by adjustable splitters placed along the edges of the table.

Sheet Piles – vertical groundwater barriers constructed by driving pilings into the formations.

Short-Residence-Time, Intensive Melters – these waste vitrification melters provide more intensive mixing, allowing the melter to be smaller.

Short-Term Effectiveness – refers to the control of adverse impacts on human health and the environment posed during the construction and implementation of an alternative until cleanup goals are achieved.

Silica Fume – very fine silica dust produced by condensation of silica fumes.

Sludge – in this document, sludge means a viscous semisolid or fluid containing contaminants requiring treatment. The regulatory definition is any solid, semisolid, or liquid waste generated from a municipal, commercial, or industrial wastewater treatment plant, water supply treatment plant, or air pollution control facility with the exception of specific exclusions such as the treated effluent from a wastewater treatment plant (40 CFR 260.10).

Slurry Walls – are constructed in a vertical trench excavated under a slurry.

Soil – loose material on the surface of the earth, as distinguished from solid rock, consisting of mineral grains and organic materials in varying proportions.

Soil Flushing – involves extraction and injection of aqueous solutions to remove contaminants from the subsurface without excavation of the contaminated materials.

Soil Washing – a broad term often used to describe any system that effects a physical or chemical separation/concentration of contaminants using a fluid.

Solid Waste – see *RCRA solid waste.*

Solidification – a process in which materials are added to the waste to convert it to a solid or to simply improve its handling and physical properties. The process may or may not involve a chemical bonding between the waste, its contaminants, and the binder. In solidification, the mechanical binding of contaminants can be on the microscale (microencapsulation, absorption, or adsorption) or the macroscale (macroencapsulation).

Solidification/Stabilization (S/S) – used in this document to encompass the variety of processes that may contribute to increased physical strength and/or contaminant immobilization.

Solubility – the maximum concentration of a substance dissolved in a solvent at a given temperature.

Solubility Product – a type of simplified equilibrium constant defined for and useful for equilibria between solids and their respective ions in solution.

Soluble Threshold Limit Concentration (STLC) – limit applied to Cal WET leaching results (Ca 22 California Code of Regulations 66699).

Solution – a single, homogeneous phase of liquid, solid, or gas in which a solute is uniformly distributed.

Sorption – a general term used to encompass the processes of adsorption, absorption, desorption, ion exchange, ion exclusion, ion retardation, chemisorption, and dialysis.

Spiral Concentrator – another popular type of gravity separator, this device consists of a helical channel that winds down a central pole. Feed is introduced at the top of the spiral as a 10 to 40% solids slurry. As the slurry flows down the spiral, a velocity gradient is created along the thickness of the water film. The water closest to the channel surface flows very slowly due to friction, whereas the velocity increases toward the top of the water film. The smallest particles submerge in the slower moving layer of the film. The larger particles and the bulk of the fluid are faster moving and are subject to centrifugal force along the curved path, which causes them to move outward.

S/S Technologies – inhibit mobility or interaction in the environment through chemical reactions and/or physical interactions to retain or stabilize the contaminants.

S/S Treated Waste – a waste liquid, solution, slurry, sludge, or powder that has been converted to a stable solid (granular or monolithic) by an S/S treatment process.

Stability – the stabilization and solidification provided by an S/S process.
Stabilization – a process by which a waste is converted to a more chemically stable form. The term may include solidification, but also includes chemical changes to reduce contaminant mobility.

Storage – the holding of hazardous waste for a temporary period, at the end of which the hazardous waste is treated, disposed of, or stored elsewhere (40 CFR 260.10).

Superfund – common name used for Comprehensive Environmental Response, Compensation, and Liability Act (CERCLA), as amended by the Superfund Authorization Act (SARA) and also used to refer to sites listed on the National Priorities list (NPL) and the Trust Fund established by the Act to fund response to releases of hazardous substances and cleanup of hazardous waste sites.

Surface Water – bodies of water that are directly accessible at the ground surface, such as rivers, lakes, streams, and ponds.

Surfactant – surface-active agent, a soluble compound that reduces the surface tension of liquids, or reduces interfacial tension between two liquids or a liquid and a solid.

Thermoplastic Resin – an organic polymer with a linear macromolecular structure that will repeatedly soften when heated and harden when cooled; for example styrenes, acrylics, cellulosics, polyethylenes, vinyls, nylons, and fluorocarbons.

Thermosetting Resin – an organic polymer that solidifies when first heated under pressure, and which cannot be remelted or remolded without destroying its original characteristics; for example epoxies, melamines, phenolics, and ureas.

Tortuosity – the ratio of the length of a sinuous pathway between two points and the length of a straight line between the points.

Total Organic Carbon (TOC) – a chemical analysis.

Total Threshold Limit Concentration (TTLC) – limit applied to Cal WET leaching results (Ca 22 California Code of Regulations 66699).

Total Waste Analysis (TWA) – total concentration of priority pollutants, organics, and metals in the waste

Toxicity Characteristic – exhibiting the hazardous characteristic of toxicity as defined in 40 CFR 261.24.

Toxicity Characteristic Leaching Procedure (TCLP) – the primary leach testing procedure required by 40 CFR 261.24 and the most commonly used test for degree of immobilization offered by an S/S process.

Transportation – the movement of hazardous waste by air, rail, highway, or water (40 CFR 260.10).

Treatability Study – a study in which hazardous waste is subjected to a treatment process to determine: (1) whether the waste is amenable to the treatment process, (2) what pretreatment (if any) is required, (3) the optimal process conditions needed to achieve the desired treatment, (4) the efficiency of a treatment process for a specific waste or wastes, or (5) the characteristics and volumes of residuals from a particular treatment process (40 CFR 260.10).

Treatment – any method, technique, or process, including neutralization, designed to change the physical, chemical, or biological character or composition of any hazardous waste so as to neutralize such waste, or so as to recover energy or material resources from the waste, or so as to render such waste nonhazardous, or less hazardous; safer to transport, store, or dispose of; or amenable for recovery, amenable for storage, or reduced in volume (40 CFR 260.10).

Triaxial Compression – compression caused by the application of normal stress in lateral directions (ASTM D 653, p. 152).

Triaxial Shear Test (triaxial compression test) – a test in which a cylindrical specimen encased in an impervious membrane is subjected to a confining pressure and then loaded axially to failure.

Trommel – cylindrical screen rotated around its centerline, used to attrition scrub and physically grade coarse particulates.

Unconfined Compressive Strength (UCS) – the load per unit area at which an unconfined cube or cylindrical specimen of material will fail in a simple compression test without lateral support.

Vertical Barriers – when placed at the perimeter of a metal-contaminated site, can reduce movement of contaminated groundwater off site or limit the flow of uncontaminated groundwater through the site.

Vitrification Technologies – technologies that apply high-temperature treatment aimed primarily at reducing the mobility of metals by incorporation in a vitreous material.

Vegetative Uptake – metals are concentrated as they are taken up through the root systems of plants and deposited in the leaves.

Volatile Organic Compound (VOC) – an organic compound with a low boiling point.

Waelz Kiln – a rotary kiln used to vaporize cadmium, lead, and zinc from a complex oxide/silicate matrix and recover the vaporized metals as mixed oxide condensed fume.

Wastewater – the water media group includes groundwater, surface water, and contaminated washwater or process water from soils, sediments, and sludge treatment processes.

Wastewater Treatment Sludge – hydroxide or hydroxide/sulfide precipitates from treatment of wastewater.

Wet/Dry Cycle – alternation of soaking and drying a sample to allow determination of material loss and visual observation of sample disintegration resulting from repeated soaking and drying cycles.

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